Inline disinfestation of canola seeds from red flour beetles using a 50-ohm RF technology

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Tolen Tombung Moirangthem

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ABSTRACT

Disinfestation of insect pests in stored grains is a crucial unit operation to save the quality of the grains during the storage. Several methods of disinfestation are available including chemical and non-chemical methods. However, the use of the chemical method is avoided because of its adverse effects on the environment and studies show that chemical methods have failed frequently in recent years. So, this research focus on investigation of the usage of radio waves, which is a non-chemical method to disinfest insects in stored grains. A pilot-scale 50-ohm radio frequency (RF) heating system was used to disinfest adult red flour beetles (*Tribolium castaneum*) in bulk canola seeds (*Brassica napus* L.) of 9 % moisture content (MC) in a tubular applicator with parallel electrodes. The heating characteristics of the bulk canola seeds was studied using the 50-ohm RF system and non-uniformity of the temperature distribution of bulk canola was observed. The hottest spot was observed at the front side of the tubular cavity of the applicator adjacent to the hot electrode. The RF heating rate depends on the distribution of the electromagnetic (EM) field, geometry, and position of the sample in the RF applicator, thermal, physical, and electrical properties of the sample. The average temperature (T_{avg}) and uniformity index (θ) of the bulk canola during RF heating were also observed. The thermal mortalities of adult red flour beetles infesting canola seeds at 9% moisture content (MC) were determined treated using a 50-ohm radio frequency (RF) heating system. The infested seeds were treated between 297 K and 338 K at RF heating power of 3 kW, 5 kW, and 7 kW. The survival rate of the adult *T. castaneum* infesting the canola seeds at 9% MC decreased with an increase in temperature (297 K to 338 K) and increase in RF power levels (3 kW to 7 kW). Desirable selective heating effect on mortality was more predominant at higher RF powers. An inverse simulation was used to estimate kinetic parameters of the thermal death of the adult *T. castaneum*. 4^{th} order Runge-Kutta method was used to solve

the ordinary differential equation (ODE) based kinetic model which has an Arrhenius temperature-dependent reaction rate constant. The thermal death kinetics of the adult *T. castaneum* followed first order reaction with an activation energy of 97.50 kJ/mol. Satisfactory agreements were observed between the mortalities predicted using the kinetic model and the experiments. Also, the physicochemical properties of canola seeds were affected by the RF heating at various end temperatures and power levels although the changes were not very significant and were in an acceptable range. Thus, the research was a successful in disinfesting adult red flour beetles in bulk canola seeds of 9% MC using a pilot-scale 50-ohm RF heating system with a tubular applicator with parallel electrodes.

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GENERAL INTRODUCTION

Radio frequency (RF) heating relies on change in orientation of polar molecules and ions when induced by high frequency electromagnetic (EM) waves. Also, RF heating depends on the features of EM energy, and the electrical, thermal, as well as physical properties of the sample. The United States Federal Communications Commission (FCC), permits the use of 13.56 MHz, 27.12 MHz, and 40.68 MHz for RF heating applications for industrial, scientific, and medical (ISM) purposes, to avoid interference in communication (Wang et al. 2011). Thus, 27.12 MHz was used in this research. One major benefit of RF heating is selective heating, so, commodities with higher dielectric loss factor heat up at much faster rate than ones with lesser dielectric loss factor (Shrestha and Baik 2013; Yu et al. 2015). Generally in food processing industries several types of RF heating systems are used and the systems are differentiated based on how the radio waves are generated and transmitted through the material being processed; two of the common RF heating systems are the free running oscillator system and the 50-ohm system (Marra et al. 2009). This research uses the 50-ohm system which comprises of an RF generator (RFG) which generates the RF energy which is transferred to a matching network through a 50-ohm cable. The matching network is connected to the electrodes through which the radio waves are generated and transferred to the materials being processed. The 50-ohm RF system produces stable frequency and power as the matching network automatically adjusts to maintain the load impedance, thus, 50-ohm systems have become popular in the food industry (Jones and Rowley 1996). Literature shows that RF heating systems have non-uniformity in distribution of temperature in the sample, so, appropriate design of RF heating systems is crucial (Yu et al. 2016). The design of the RF applicator is determined by the electric field pattern being generated in between the electrodes, some common types of RF applicator designs are through field type, fringe filed type, and staggered through field type (Jones and Rowley 1996). The through field type applicator was used in this research, the applicator is comprised of parallel plates electrodes (anode and ground) and the samples were introduced between the electrodes to complete the parallel capacitor circuit. This applicator design was chosen as a through field type applicator is ideal for heating larger bulk materials. As described by Huang et al. (2018), the mechanism of the parallel plate type applicator is based on high voltage being introduced in the anode electrode and completing the circuit in the ground electrode while forming circulation of EM waves in between the electrode and triggering selective heating in the sample (Huang et al. 2018).

Canola is an important global oilseed crop. The chief producers of canola seed include China, India, Canada, and the European Union. World production in 2018-2019 was 72.80 million metric tons and according to USDA (2019) is expected to be 74.80 million metric tons in 2019-2020 (USDA Foreign Agricultural Service 2019). About 90 % of the total production of canola in Canada is exported around the world, and Canadian economy faces a crucial challenge, 8% to 10% in annual crop yield is lost due to insect pests (Canola Watch 2015). Thus, a quick and effective disinfestation process and RF heating has the potential to solve the problem. Along with economic losses, insect pest infestation is a considerable barrier to export and constitutes a significant concern in the production, storage, and the process of all food products (Gao et al. 2010). The trade regulations of domestic and international markets have required postharvest treatments of all food products to ensure quarantine security from insect pests (Birla et al. 2008; Jiao et al. 2011). Thus, development of an effective technique that can handle larger sample sizes in quick time for disinfestation of insects from canola seeds is critical.

The objective of this study is to develop a disinfestation protocol to disinfest adult *Tribolium castaneum* in stored canola seeds using 50-ohm RF heating system with through field parallel plate type electrodes. Thus, to achieve the main objective the study was divided into sub-objectives which are as described below:

1. Critical review on different types of disinfestation techniques available in the grain processing industries.
2. Temperature distribution in a packed bed of canola seeds during 50-ohm RF heating at various power levels using a 50-ohm RF heating with parallel plate type applicator.
3. Immediate mortality of adult *Tribolium castaneum* in stored canola, at 9% MCs and end temperatures of the host grains during RF heating at 3 kW, 5 kW, and 7 kW at 27.12 MHz.
4. Physicochemical properties of canola seeds before and after the RF treatment that resulted in 100% mortality of insect pests, which include MC, germination rate, colour, and oil quality before and after the RF treatment.

Outline of the Thesis

The thesis is journal paper based and each individual paper represents a thesis chapter. The first chapter is based on critical review on different types of disinfestation techniques used in disinfestation of stored grains especially using non-chemical methods. This chapter was submitted to *Trends in Food Science and Technology*, a research journal and is under revision as suggested by the chief editor of the journal. The second chapter is methods for determination of heating characteristics during 50-ohm RF heating of bulk canola seeds (*Brassica napus*. L) in a tubular type applicator with parallel plate electrodes and examination of physiochemical properties of *Brassica napus* (L.) before and after the RF treatment. This chapter was submitted to the *Innovative Food Science and Emerging Technologies* research journal. The third chapter discusses about the thermal death kinetics of red flour beetle (*Tribolium castaneum*) in stored *Brassica napus* (L.) seeds using the pilot-scale 50-ohm RF heating system to understand desirable selective heating effect on mortality at different RF power levels. This chapter was submitted to the *Food and Bioproducts Processing* research journal. The fourth chapter discusses the general application of the general finding in the 50-ohm RF heating with parallel plate type applicator for disinfestation of *Tribolium castaneum* in stored *Brassica napus* (L.) seeds, and recommendation for future studies.

References

Birla, S. L., S. Wang, J. Tang and G. Tiwari. 2008. Characterization of radio frequency heating of fresh fruits influenced by dielectric properties. *Journal of Food Engineering,* 89(4):390-398.

Canola Watch. 2015. http://www.canolawatch.org/2011/05/09/estimating-flea-beetle-damage-in-canola/ . (2019/05/18).

Gao, M., J. Tang, Y. Wang, J. Powers and S. Wang. 2010. Almond quality as influenced by radio frequency heat treatments for disinfestation. *Postharvest Biology and Technology*, 58(3):225-231.

Huang, Z., F. Marra, J. Subbiah and S. Wang. 2018. Computer simulation for improving radio frequency (RF) heating uniformity of food products: A review. *Critical Reviews in Food Science and Nutrition,* 58(6):1033-1057.

Jiao, S., J. A. Johnson, J. Tang, G. Tiwari and S. Wang. 2011. Dielectric properties of cowpea weevil, black-eyed peas and mung beans with respect to the development of radio frequency heat treatments. *Biosystems Engineering*, 108 (3):280-291.

Jones, P. L. and A. T. Rowley. 1996. Dielectric drying. *Drying Technology*, 14:1063–1098.

Marra, F., L. Zhang and J. G. Lyng. 2009. Radio frequency treatment of foods: review of recent advances. *Journal of Food Engineering*, 91:497–508.

Shrestha, B., D. Yu and O. D. Baik. 2013. Elimination of *Cryptolestes ferrugineus* S. in wheat by radio frequency dielectric heating at different moisture contents. *Progress in Electromagnetics Research*, 139:517-538.

USDA (United States Department of Agriculture). 2019. Stored Grain Insects. Federal Grain Inspection Service United States Department. https://www.gipsa.usda.gov/

Wang, Y., Y. Li, S. Wang, L. Zhang, M. Gao and J. Tang. 2011. Review of Dielectric Drying of Foods and Agricultural Products. *International Journal of Agricultural and Biological Engineering*, 4(1):1–19.

Yu, D., B. L. Shrestha and O. D. Baik. 2016. Temperature distribution in a packed bed of canola seeds with various moisture contents and bulk volumes during radio frequency (RF) heating. *Biosystems Engineering*, 148:55-67.

Yu, D. U., B. L. Shrestha and O. D. Baik. 2015. Radio Frequency Dielectric Properties of Bulk Canola Seeds under Different Temperatures, Moisture Contents, and Frequencies for Feasibility of Radio Frequency Disinfestation. *International Journal of Food Properties*, 18(12):2746-2763.

CHAPTER 1

Disinfestation of stored grains using non-chemical technologies – A review

Contribution of this chapter to overall study

This thesis is based on disinfection stored food grains from insect pests and the knowledge of different types of disinfestation techniques used in food grain storage is crucial. This chapter serves as a review of literature of the overall study, detailing the popular techniques using non-chemical methods to eliminate insect pests in stored grains. The basic principles, advantages, and disadvantages of some of the popular techniques such as ionizing radiation, modified atmosphere, and dielectric heating used for disinfestation of stored grains are discussed in this chapter. Also, this chapter includes the scope and opportunities of dielectric heating (microwave, and radio frequency) in grain processing industries for disinfestation of insect pests in stored grains. The review and the journal paper manuscript were drafted by me.

1.1 Abstract

Disinfestation of insect pests is a crucial unit operation to preserve the quality of food grains during the storage. Several approaches for disinfestation are available including chemical and non-chemical methods. However, the use of the chemicals is often avoided because of potential adverse effects on the environment and studies that show chemical methods have failed. This chapter reviews recent applications of ionizing radiation, modified atmosphere, and dielectric heating for

disinfestation of stored grains. It is noted that the technologies mentioned have numerous advantages, however, these also can cause adverse effects to the grains being treated. To maximize treatment efficiency, the systematic integration of multiple non-chemical disinfestation methods with other unit operations is recommended.

1.2 Nomenclature

$\Delta T/\Delta t$	rate of change of temperature
^{137}Cs	Cesium-137
^{60}Co	Cobalt-60
c	speed of light in free space (3×10^8 m s^{-1})
C_p	specific heat (J $kg^{-1}C^{-1}$)
E	electric field strength (V m^{-1})
EM	electromagnetic wave
f	frequency (Hz)
IPM	international pest management
IR	infrared
LT	lethal time (s)
MA	modified atmosphere
MC	moisture content (%)
MW	microwave

P_{avg} average power density (W m^{-3})

P_d penetration depth

PEI polyetherimide

RF radio frequency

RH relative humidity (%)

USDA United States Department of Agriculture

UV ultraviolet

w.b. wet basis (%)

WHO World Health Organisation

ε permittivity

ε' dielectric constant

ε'' dielectric loss factor

ε° vacuum permittivity (8.85×10^{-12} F m^{-1})

ε_d'' dipole rotation loss

ε_σ'' ionic conduction loss

ρ bulk density (kg m^{-3})

θ uniformity index

λ wavelength (m)

1.3 Introduction

Disinfestation of insects in grains is an important unit operation during storage and handling of grains. Insect attacks are accountable for calculable loss of one-third of total grain production (Government of Western Australia, 2018). Since the 1950s, chemical disinfectants have been a popular choice for disinfestation, for example, global expenditure on chemical disinfestation processes was over 30 billion US dollars during the year 1990 to 2000 (Gannage, 2000). Some common chemical disinfectants are $C_{10}H_{19}O_6PS_2$, $C_7H_7C_{13}NO_3PS$, and $C_{22}H_{19}Br_2NO_3$ which are considered as contact pesticides and MeBr and PH_3 which are considered as fumigants (Sinha and Watters, 1985; Bond, 1985). However, use of certain chemical disinfectants such as MeBr is banned since 2005 in developed countries, and since 2015 in developing countries due to adverse effects on human health and the environment (Leesch, 2000; UNEP, 1997). Similarly, PH_3, $C_{10}H_{19}O_6PS_2$, and fumigants are shown to be ineffective by several researchers, as insects develop immunity against the chemical disinfectants, and these chemicals did not harm the insect eggs especially the ones hidden within grain kernels (Sinha and Watters, 1985). Thus, the replacement of chemical disinfectants is necessary with other non-chemical disinfestation processes which are more efficient and have a less negative impact on the physicochemical properties of grains being treated, human health, and the environment. Some popular non-chemical disinfestation processes, which are popular and have immense potential to make a positive impact in grain storage and handling processes, applying ionizing radiation, modified atmosphere (MA), and dielectric heating.

Irradiation is used against stored-product pests by direct treatment of the commodities, providing a residue-free process of pest control and by genetically controlling male insects. Generally, the most common apparatus for an MA treatment involves treatment of the grains in a controlled chamber facility. MA disinfestation process involves altering the environmental conditions of the infested stored grains by modifying the gases (O_2, N_2, and CO_2) concentration, relative humidity (RH), and atmospheric pressure. Combination of all the parameters involved in MA disinfestation process is altered in such a manner that the respiration rate of insects is affected, which leads to deaths of insects with minimum deterioration of physicochemical properties of the grains (Navarro, 2012). Disinfestation using irradiation process is based on dominant lethal mutation of sperm of the male insects and infecundity in all female ones, thereby controlling the population of insects infesting stored grains (Klaseen, 2005). Dielectric heating is an emerging technology for disinfestation of insects in stored grains. Dielectric heating is based on electromagnetic (EM) radiation which relies on the dielectric properties, physical properties, specific heat, and bulk density of the sample. The dielectric properties, physical properties, specific heat, and bulk density of the insects and the grains are different, and the power dissipation boosts a higher temperature increment rate in insects relating to that of the grains (Shrestha et al., 2013). Therefore, dielectric heating is predicted to kill insect pests without hampering the physiochemical properties of the grains significantly (Shrestha et al., 2013). Volumetric and selective heating are the major advantages of dielectric heating. Some other nonchemical treatments to control insect pests include convective heating by hot air and cold storage, however these techniques require a longer treatment time and a substantial capital investment and may sometimes leave live insect pests after the treatments (Heather and Hallman, 2008).

The insect pests found in stored grains are usually classified as primary and secondary pests. Primary insect pests are either found as a group of a particular species or as a group of different species, they feed upon the embryo of grains which is a vital part of any grain and has all the vital nutrients (Government of Western Australia, 2018; USDA, 2015). Secondary insects, on the other hand, coexist with the primary insects and feed upon the leftovers damaged grains mainly caused by the primary insects and during the handling and storage of the grains. Secondary insects can be effectively removed during the cleaning process along with the broken and damaged grains before storing the grains (USDA, 2015). Thus, any disinfestation process is dedicated to eliminating primary insects in stored grains. However, the classification of primary and secondary insects may differ based on the topography and the types of grains grown in that zone (Government of Western Australia, 2018; USDA, 2015; Canadian Grain Commission, 2020). Table 1.1 shows the list of primary insects classified by the Canadian Grain Commission, United States Department of Agriculture, and Government of Western Australia. Figure 1.1 shows the pictures of the common primary insects in all the three departments (Government of Western Australia, 2018; USDA, 2015; Canadian Grain Commission, 2020).

Apart from irradiation, MA, and dielectric heating there are several other non-chemical processing methods for disinfestation of agricultural products other than food grains from primary insect pests, such as cold plasma processing, electron beam technology, and soft electron (low-energy electrons). Although these technologies have potential in being implemented to successfully disinfest food grains, literature does not show enough evidence to analyze the major advantages and disadvantages compared to the ones mentioned in this chapter. Thus, this chapter focuses on the working principles, advantages, and disadvantages of the popular techniques of non-chemical disinfestation of stored food grains which include ionizing radiation, MA, and dielectric heating.

Table 1.1: List of primary insects classified by Canadian Grain Commission, United States Department of Agriculture, and Government of Western Australia.

Serial no.	Department	Primary insects
1	Canadian Grain Commission	*P. truncatus* (Horn)
		R. dominica (Fauvel)
		A. obtectus (Say)
		B. pisorum (Linnaeus)
		C. chinensis (Linnaeus)
		S. granarius (Linnaeus)
		S. oryzae (Linnaeus)
		S. zeamais Motschulsky
		T. granarium Everts
		C. ferrugineus (Stephens)
		C. pusillus (Schönherr)
		C. turcicus (Grouvelle)
		O. mercator (Fauvel)
		O. surinamensis (Linnaeus)
		L. oryzae Waterhouse
		T. castaneum (Herbst)
		T. confusum (Jaquelin du Val)
		T. destructor Uyttenboogaart
		T. mauritanicus (Linnaeus)
		S. cerealella (Olivier)
2	United States Department of Agriculture	*S. granarius* (Linnaeus)
		S. oryzae (Linnaeus)
		S. zeamaise (Motschulsky)
		R. dominica (Fabricius)
		S. cerealella (Olivier)
3	Government of Western Australia	*R. dominica*
		S. oryzae
		S. granarius
		S. cerealella

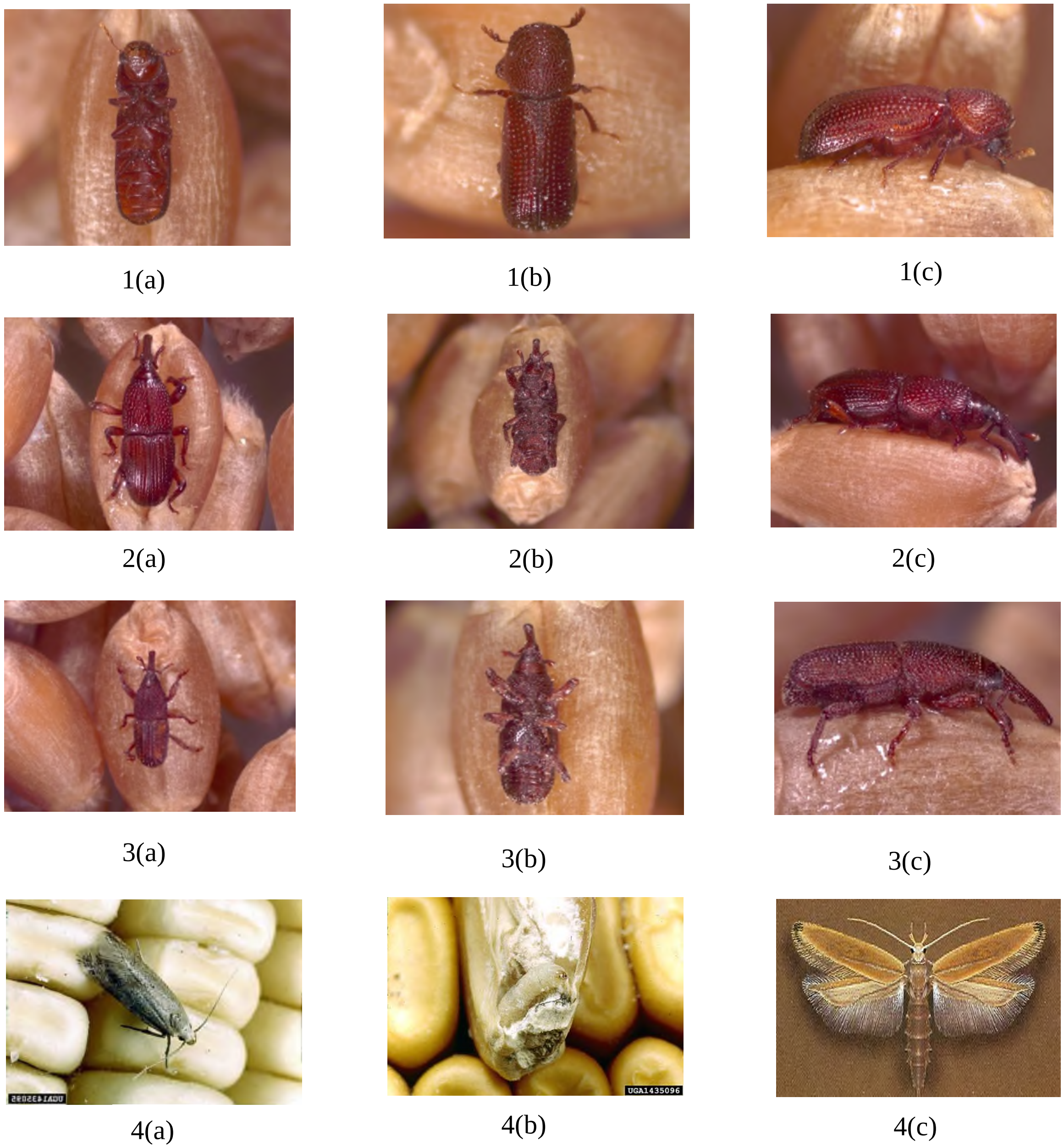

Figure 1.1: Images of insects considered as primary insects by Government of Western Australia, USDA, and Canadian Grain Commission 1(a) dorsal, 1(b) ventral, and 1(c) lateral view of *R. dominica*, 2(a) dorsal, 2(b) ventral, and 2(c) lateral view of *S. oryzae*, 3(a) dorsal, 3(b) ventral, and 3(c) lateral view of *S. granarius*, 4(a) adult *S. cerealella* infested grains, 4(b) larve of an *S. cerealella* on infested grains, 4(c) dorsal view of adult *S. cerealella*. Adapted from Canadian Grain Commissions (2020) and Clemson Univ./USDA CES Bugwood.org.

1.4 Non-chemical disinfestation methods

The working principles, literature review, and the concluding remarks of some popular non-chemical methods use in disinfestation of insect pests in stored grains are listed below. The non-chemical methods for disinfestation include ionizing radiation, MA, and dielectric heating.

1.4.1.1 Ionizing radiation

Irradiation doses define the degree of distruction of spermatogonia in male insects and oogonia or trophocytes for egg formation (Klaseen, 2005). During irradiation breakage of chromosome induced in the germ cells causes dominant lethal mutation of sperm of the male insects (Klaseen, 2005). Along with irradiation doses, the effects of irradiation on insects are defined by species type, life stages, age, and physiological state of the insect (Tilton and Brower, 1983). Ionizing radiations are produced by displacing the electrons from the atoms, and molecules of the material, and converting them to electrically charged ions (Riganakos, 2010). There are several methods to generate ionizing radiations, however, the approved radiation doses to eradicate infestations of pests by the Food and Drug Administration in the USA are gamma-rays of ^{60}Co (1.17 and 1.33 MeV), ^{137}Cs (0.662 MeV), x-rays (< 5 MeV), and electron beams (<10 MeV) with a radiation dose of 1000 Gy (Codex Alimentarius Commission, 2003). The radiation dose absorbed is relevant to the absorbed energy per unit mass of material, thus, the amount of radiation exposure determines the effectiveness of the process (Cleland, 2013). The SI unit of ionizing radiation is gray (Gy) and 1 Gy = 1 J/kg. Also, another common unit of ionizing radiation is rad (1 Gy = 100 rad), the use of rad is found in industries and pieces of literature.

A general food irradiation facility consists of several features as shown in Figure 1.2, and some of the crucial features include radiation generator, irradiation chamber, shielding around the irradiation chamber to eliminate any potential harm to the workers due to the radiation exposure, a transport system to get the food materials to the irradiation chamber, air evacuation system, and safety system to ensure all the unit operations in the irradiation system is safe to the workers to avoid any consequences (Fiszer, 1988).

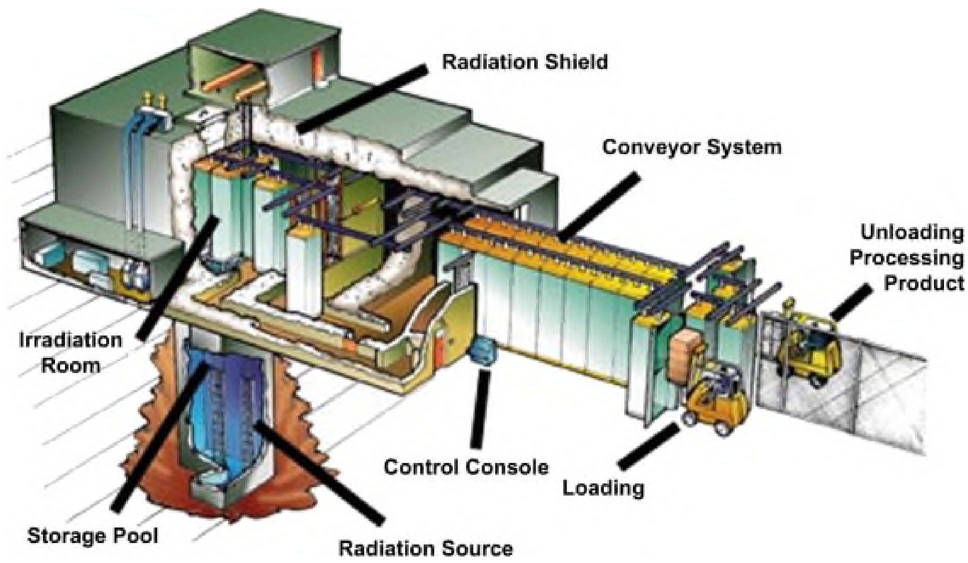

Figure 1.2: Pallet-type commercial ^{60}Co irradiation facility (courtesy of Nordion International Inc., Ontario, Canada). Adapted from Fiszer (1988)**.**

The term irradiation is used to represents all non-ionizing energy-based systems which include radar, infrared (IR), ultraviolet (UV), x-rays, and gamma-rays in this chapter.

1.4.1.2 Ionizing radiation application in disinfestation

Table 1.2 shows approximate irradiation doses for different life stages of primary insect pests to inhibit development of immatures. The recommendations on irradiation doses shown in Table 1.2 are based on confirmatory studies done on large number of test insect species infesting stored food grains published by several researchers (IAEA, 2004; Ahmed, 1990). Adult insects of *S. cerealella* and *O. surinamensis* are more resistant to irradiation compared to other stages in the developmental sequence, requiring up to 0.25±0.40 kGy for complete elimination (Hasan and Khan, 1998). *S. zeamais* and *C. maculatus* in maize and cowpea can be successfully disinfested using ^{60}Co gamma cells, with irradiation doses ranging from 0.2 kGy to 0.5 kGy, with no significant effect in germination rate of the grains (Enu and Enu, 2014). ^{60}Co cells can penetrate up to 50 cm into bulk grains, effectively killing insect pests of all life stages of *S. zeamais, C. maculatus, C. chinensis (L), S. zeamais,* and *S. oryzae* without effecting the odor, taste, and appearances of grains (Enu and Enu, 2014; Bhuiya et al., 1991). Bhuiya et al. (1991) and Hasan et al. (1998) reviewed effects of acute doses of ionizing radiation against adult insects and summarized as: very high doses are required for immediate death (> 1kGy). The authors also added that many days' delay may occur before the first signs of mortality; death is then usually quite sudden, and any survivors may then live longer than the controlled ones. Bhuiya et al. (1991) and Hasan et al. (1998) also added that adult becomes more susceptible with advancing age and young adults are comparable with late pupae in susceptibility to radiation sterilisation. Deformity is overserved to be related to irradiation dose and survival time of adults with severe deformity was shorter than adults with slight deformity (Bhuiya et al., 1991; Hasan et al., 1998). Hassan and Khan (1998) also concluded the following:

- larvae are more resistant to radiation than eggs
- variation in the susceptibility between larval stages
- irradiation causes prolonged larval development and delayed pupation

- greater mortality can be achieved by irradiating larvae that are about to moult or pupate

Table 1.2: Approximate irradiation doses for different life stages of primary insect pests to inhibit development of immatures.

Insect species	Stages	Doses (kGy)
A. obtectus	Eggs, larvae, pupae, and adults	0.30
C. chinensis	Eggs, larvae, pupae, and adults	0.10
O. mercator	Eggs, larvae, pupae, and adults	0.20
O. surinamensis	Eggs, larvae, pupae, and adults	0.70
P. truncatus	Eggs, larvae, pupae, and adults	0.12
R. dominica	Eggs, larvae, pupae, and adults	0.12
S. cerealella	Eggs, larvae, pupae, and adults	0.60
S. granarius	Eggs, larvae, pupae, and adults	0.08
S. oryzae	Eggs, larvae, pupae, and adults	0.08
S. zeamais	Eggs, larvae, pupae, and adults	0.16
T. castaneum	Eggs, larvae, pupae, and adults	0.12
T. confusum	Eggs, larvae, pupae, and adults	0.20
T. destructor	Eggs, larvae, pupae, and adults	0.20
T. granarium	Eggs, larvae, pupae, and adults	0.25

Note: Adapted from IAEA (2004) and Ahmed (1990).

Irradiation is found to be successful in disinfesting insect pests in stored grains although literature also shows negative impacts on irradiated stored grains. So, important factors that must be considered in an effective irradiation insect pests control programme are the application costs and the adverse effects on grains. Germination of barley and wheat decreases when the irradiation doses are higher than 6.25 krad and 25 krad respectively, however, shows no negative impact on nutritional value of whole wheat grains and wheat flour (FDA, 1981). γ-rays irradiation using ^{60}Co has both positive and negative impacts on the nutritional components of wheat grains. Different γ-rays irradiation doses (0.01 kGy, 0.03 kGy, 0.05 kGy, and 0.10 kGy) using ^{60}Co increase the N_2, K, Cu, protein, carotenoid, and nucleic acid contents but decreases the P, Fe, Zn, Mn and starch content in wheat grains (Singh and Datta, 2010). Although consideration of adverse effects of irradiation on the nutritional content of grains is curial in designing an effective irradiation disinfestation protocol, irradiation also adversely effects the anti-nutritional properties of the grains. Anti-nutrient components (protease inhibitors, lectin, phytic acid, non-starch polysaccharides, and oligosaccharides) in grains can be effectively deactivated by exposing the grains to irradiation levels of up to 10 kGy without any undesirable post-treatment quality changes to the grains (Sindhuraju et al., 2002).

1.4.1.3 Remarks on disinfestation using ionizing radiation

Irradiation processes with doses below 1 kGy do not affect genetic and biochemical properties of grains and effective irradiation dose range for disinfestation of insects in grains is 0.2 kGy to 0.8 kGy (Farkas and Farkas, 2011). When doses are above 10 kGy toxicological analyses become critical to understand the effectiveness of irradiation process in disabling anti-nutrients and other consequences on nutritional quality of stored grains (Sindhuraju et al., 2002).

So, physio-chemical properties in grains are affected by irradiation depending on irradiation doses and variety of grains. Understanding the balance between usefulness and adverse effects of irradiation is important. According to WHO, "food irradiation is a thoroughly tested technique, that it has not been shown to have any deleterious effects when performed in accordance with good manufacturing practice and that it can help to ensure a safer and more plentiful food supply by extending shelf-life, eradicating pests, and inactivating pathogens" (WHO, 1994). The use of irradiation technology in disinfestation of grains is safe and some countries use this technology commercially. It has been recorded that most countries use radiation facilities for preservation of fruits, vegetables, packed meat, animal feed, spices, marine products, and food grains (Das et al, 2013). In recent years, there has been a tremendous development in irradiation research, and it is hoped that newer technologies will be discovered in integration with irradiation (Das et al., 2013).

This will help in minimizing the cost of a treatment facility and reduce the adverse effects of such ionizing radiation on food when treated.

1.4.2.1 Modified atmosphere

MA improves shelf life of grains by altering the surrounding atmospheric condition. Alternations in atmospheric conditions heavily rely on the composition of gases present, which affects the respiration rate of grains and insect pests. Generally, the most common set up for an MA treatment involves treatment of grains in a controlled chamber facility where O_2 present is regulated to be lower in quantity and CO_2 content is enhanced, to a situation where the biological processes of insects and grains are interrupted. In this chapter, MA refers to all the processes that involve alteration in the composition of atmospheric gases and partial pressures to create ideal conditions for disinfestation of insect pests in stored grains.

1.4.2.2 Modified atmosphere application in disinfestation

Attacking the respiration rates of insects by controlling and modifying different components of the atmosphere is the key principle behind MA disinfestation process. Disinfestation of insects in stored grains using MA involves treatment of samples in a controlled chamber. Since O_2 plays an important parameter in insect lives. Increasing CO_2 and decreasing O_2 in the controlled chamber is one of the simplest and effective way of controlling all the life stages insects like *T. glabrum* (Herbst), *S. oryzae* (L.), *P. interpunctella* (Hübner), and *Sitophilus spp*. in stored grains (Marzke et al., 1970; Annis, 1987; De Carli et al., 2010). High CO_2 levels open the spiracles of insects causing water loss resulting in insect death, particularly when CO_2 concentration is above 10%, spiracles tend to stay permanently open (Navarro, 2012). CO_2 also damages the nervous system of insect and acidify the hemolymph leading to membrane failure in tissues and some initial symptoms may include narcotic effect leading to immobilization of insects (Navarro, 2012). Thus, exposure of insects in higher CO_2 levels for extended periods disturb the proper growth and reproduction on insect population and when CO_2 content in the MA environment is beyond 60% death of insects increase rapidly (Navarro, 2012). Similar results can be seen in Table 1.3, the number of days to achieve 95% mortality of some primary insect species at different life stages decreases as the CO_2 content in the air mixture increases. Also, Table 1.3 shows that the number of days to achieve 95% mortality of some primary insect species at different life stages increases as O_2 content in the air mixture increases.

Table 1.3: Approximate days to achieve 95% mortality of some primary insect species at different life stages using various concentrations of O_2 and mixtures of CO_2 and air (temperature range 20°C-29°C).

Insect species	Stages	% O_2				% CO_2			
		0.0	1.0	2.0	3.0	20.0	40.0	60.0	80.0
C. ferrungineus	Eggs	-	-	-	4.0	-	-	<4.0	<4.0
C. ferrungineus	Larvae	-	-	-	4.0	-	-	<4.0	<4.0
C. ferrungineus	Pupae	-	-	-	4.0	-	-	<4.0	<4.0
C. ferrungineus	Adult	<2.0	-	-	4.0	-	<13.0	<4.0	<3.0
E. cautella	Egg	1.5	1.5	-	-	-	-	-	-
E. cautella	Larvae	1.0	0.5	-	4.0	4.0	-	<5.0	-
E. cautella	Pupae	<2.0	1.0	-	-	-	-	<3.0	-
E. cautella	Adult	0.5	0.5	-	-	-	-	<2.0	-
O. surinamenis	Egg	-	-	-	4.0	-	-	<4.0	<4.0
O. surinamenis	Larvae	-	-	-	4.0	-	-	<4.0	<4.0
O. surinamenis	Pupae	-	-	-	4.0	-	-	<4.0	<4.0
O. surinamenis	Adult	<1.0	-	-	4.0	14.0	<14.0	<3.0	<3.0
P. interpunctella	Eggs	1.5	3.0	3.0	>4.5	2.5	3.0	-	-
P. interpunctella	Larvae	1.5	>4.0	>4.0	>4.0	2.0	>1.5	-	-
P. interpunctella	Pupae	3.0	3.0	6.0	>7.0	-	<3.0	<3.0	<3.0
P. interpunctella	Adults	1.0	<7.0	12.5	>14.0	-	<7.0	<7.0	<7.0
R. dominica	Eggs	-	>4.0	-	-	4.0	-	-	-
R. dominica	Larvae	-	-	-	4.0	-	-	<4.0	<4.0
R. dominica	Pupae	-	-	-	4.0	-	-	<4.0	<4.0
R. dominica	Adults	2.0	>4.0	>4.0	>4.0	7.0	4.0	1.5	<1.5
S. granaries	Adults	5.0	16.0	17.0	>17.0	20.0	6.5	6.5	2.5
S. oryzae	Eggs	9.0	<7.0	<7.0	14.0	15.5	4.5	3.5	3.5
S. oryzae	Larvae	-	-	-	-	>14.0	>7.0	3.0	2.0
S. oryzae	Pupae	20.0	<14.0	>14.0	>14.0	>14.0	8.5	6.0	8.5

S. oryzae	Adult	4.5	8.5	>21.0	>21.0	7.0	3.0	1.5	1.0
S. zeamais	Adult	2.0	-	11.5	14.0	<14.0	14.0	-	-
T. castaneum	Eggs	2.5	1.5	3.0	4.0	>4.0	2.0	<2.0	<2.0
T. castaneum	Larvae	1.5	6.5	>14.0	>14.0	>16.5	16.5	<7.0	<7.0
T. castaneum	Pupae	4.0	>3.0	-	-	-	-	3.0	<5.0
T. castaneum	Adults	1.5	6.0	>14.0	<14.0	>5.0	>14.0	1.5	3.0
T. confusum	Eggs	-	-	-	<4.0	-	-	<4.0	<4.0
T. confusum	Larvae	-	-	-	<4.0	-	-	<4.0	<4.0
T. confusum	Pupae	-	-	-	<4.0	-	-	<4.0	<4.0
T. confusum	Adults	4.5	>7.0	>7.0	<7.0	9.0	3.0	3.5	2.0
T. glabrum	Adults	-	<3.5	<3.5	<3.5	<3.0	<3.0	<3.0	<3.0
T. glabrum	Larvae	-	<3.5	<3.5	<3.5	<3.0	<3.0	<3.0	<3.0
T. granarium	Larvae and diapause	12.0	-	-	-	>25.0	>25.0	>25.0	>25.0
T. granarium	Pupae	4.0	-	-		-	-	-	5.0

Note: "<" and ">" represents the shortest time and longest time with observation of mortality greater than 95% respectively. "-" represents no reliable data available. Adapted from Riudavets (2009) and Banks and Annis (1990).

Lowering the pressure of the environment also has a positive impact on disinfestation of insect pests in stored grains. Generally, increasing the pressure reduces the exposure time and higher the temperature, faster mortality is achieved under a given atmosphere. However, literature shows that lowering of pressure increased the mortality of the insects. Different life stages of the insects react differently, and the adult insects tend to be the most vulnerable to low pressure treatments (Finkelman et al., 2006; Mbata et al., 2005). Likewise, pupae and eggs of insects are more tolerant to low pressure environment as compared to adult insects, thus requiring either increase in exposure time, temperature, or both to effectively eliminate all different life stages of insects from stored grains (Finkelman et al., 2006; Mbata et al., 2005). Along with use of different concentrations of different gases, lower RH also helps the disinfestation process using MA (Jay et al., 1971).

The application of MA in insect disinfestation is proven successful, however, there are reports which state otherwise. Insects in stored grains may have genetic potential to adapt and grow in

MA environment for example Bond and Buckland (1979) discovered that populations of *S. granarius* increased after an MA treatment. This finding can be considered as one of the major disadvantages of using MA for disinfestation. Apart from this, change in physio-chemical properties of the stored grains should also be considered, for example, changes in properties like germination of maize stored as reported by Njoroge et al. (2014). Prasntha et al. (2014) also found decrease in sensory values, as well as thiamine, and niacin contents of rice. So, contradiction of the above studies suggests that the effect of pressure in MA on disinfestation of stored grains insect pests depends on type of target insect, their life stage, and grain type.

1.4.2.3 Remarks on disinfestation using modified atmosphere

Concentration of O_2, CO_2, and N_2 are very important parameters as they contribute to alteration of pressure in the system producing desirable effects in insect pests' disinfestation process. Lowering RH enhances disinfestation of pest insects in stored grains. However, in a practical scenario infested harvested bulk grains and insect pests are difficult to distinguish, so an instantaneous and a diverse technology is preferred. Moreover, MA technology is very much target specific, so designing different systems for treatment of only one grain is an expensive procedure. Therefore, a combination of different other technologies along with MA can help optimize disinfestation process.

1.4.3.1 Dielectric heating

Dielectric heating process is based on change in orientation of polar molecules and ions (shown in Figure 1.4) when high frequency electromagnetic (EM) waves are introduced and relies on the properties of the EM energy along with the electrical, thermal, and physical properties of the sample (Tang, 2000; Wang et al., 2001a, 2001b). Radio waves and microwaves (MW) have the required wavelength and frequency to show the characteristic of dielectric heating in a sample. However, the United States Federal Communications Commission (FCC), permits the use of 13.56 MHz, 27.12 MHz, and 40.68 MHz for RF heating applications and 915 MHz, 2450 MHz, 5800 MHz, and 24125 MHz for MW heating in industrial, scientific, and medical (ISM) segments, to eliminate interference in communication (Wang et al., 2011). Comparing the wavelengths (λ) of RF heating frequencies to MW heating frequencies (shown in Figure 1.3), RF λ is greater than that of MW, thus RF waves can penetrate through larger sample sizes.

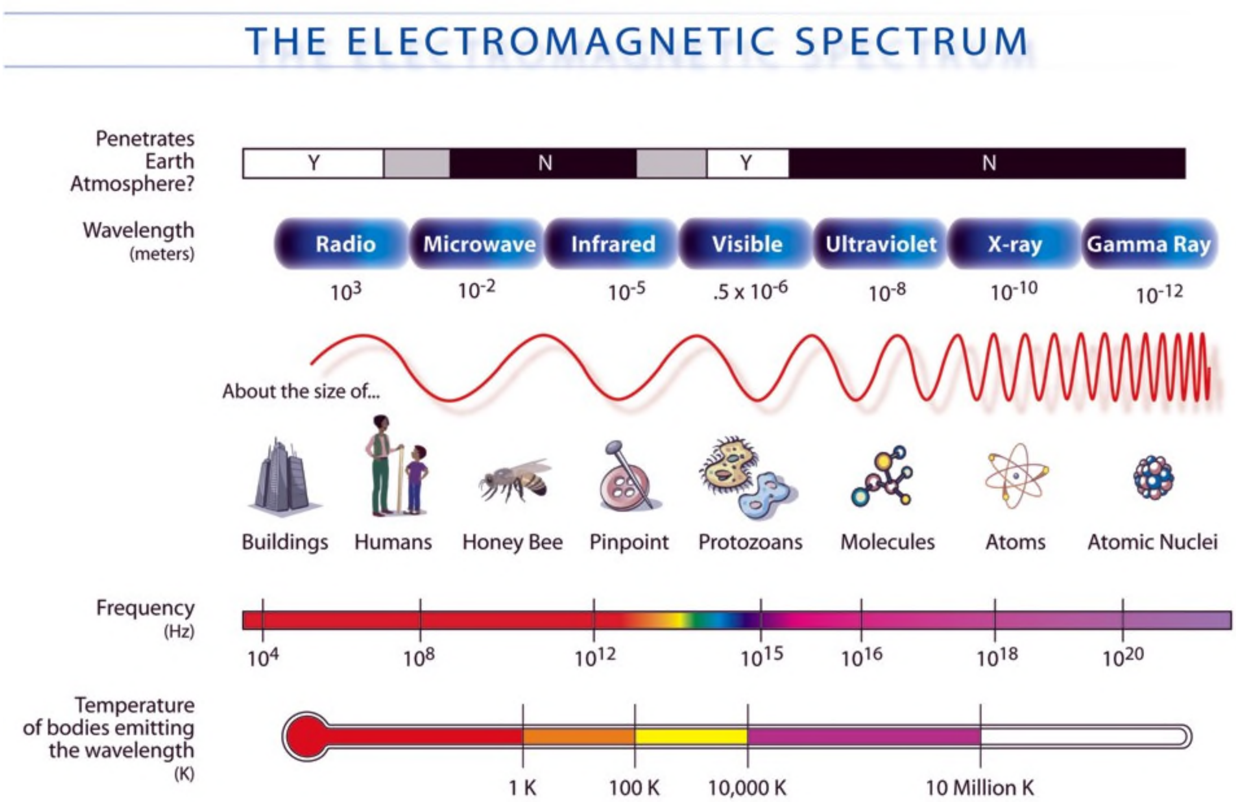

Figure 1.3: The electromagnetic spectrum. Adapted from My NASA Data (2018).

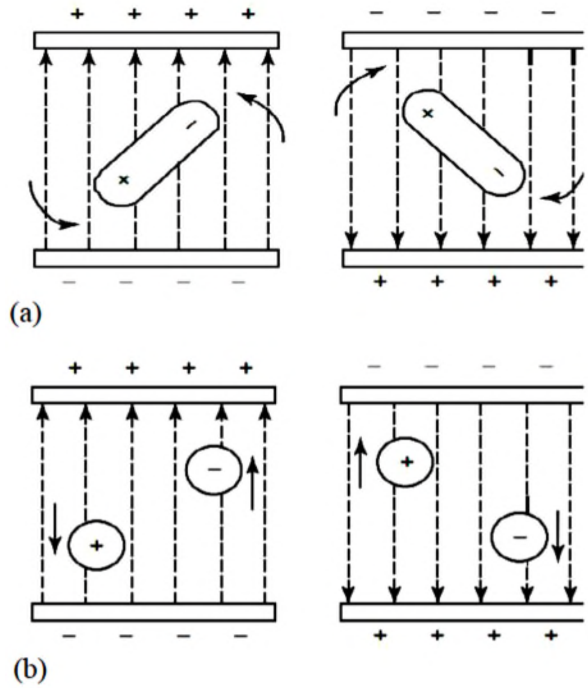

Figure 1.4: Heat conversion due to (a) dipole rotation and (b) ionic conductivity. (Adapted from Yam & Lai, 2004).

The permittivity (ε) of a dielectric material is defined as (Choi and Konrad, 1991):

$$\varepsilon = \varepsilon' + \varepsilon'' \qquad (1.1)$$

Where, ε' is the dielectric constant of the material which defines the polarization of a material or the ability of a material to store electrical energy or charges within the applied EM field. ε″ is the heat dissipation quantity of a material by conductive loss of dipolar (ε_d''), ionic charges (ε_σ''), or the ability of a material to dissipate electrical energy into heat energy compared to vacuum. In addition, ε″ is the sum of ε_d'' and ε_σ''

$$\varepsilon'' = \varepsilon_d'' + \varepsilon_\sigma'' \qquad (1.2)$$

The penetration depth (P_d) of an EM wave within a dielectric material is determined by the frequency and the dielectric properties of the material in free space (Von Hippel, 1954). The equation to estimate P_d (Stratton, 2007) is as followed:

$$P_d = \frac{c}{2\pi f} \frac{1}{\sqrt{2\varepsilon'}[1+\sqrt{(\varepsilon''+\varepsilon')^2}-1]} \text{.................................. (1.3)}$$

The ratio of temperature increment rate of insect to that grain seed can be estimated by following the procedure described by Von Hippel (1954). The average power generated inside a material can be calculated as shown in Equation (1.4) (Choi and Konrad, 1991):

$$P_{avg} = 2\pi\varepsilon^{\circ} f E^2 \varepsilon'' = \rho c_p \frac{\Delta T}{\Delta t} \text{ .... (1.4)}$$

From equation 1.4, the commodities with higher ε" will generate higher power compared to the ones with lower ε" at identical EM wave exposure. Power dissipated encourages a superior rate of temperature increment in insects compared the host grain as physical properties, specific heat, and bulk density are different. ε" of insects is higher than that of the stored grains, thus dielectric heating is predicted to kill insect pests with a lesser increase in temperature of stored grains (Shrestha et al., 2013). Bulk density of the grain is an important parameter in dielectric heating due to existence of void fraction and its effect on dielectric properties. As grains are stored in bulk, the dielectric properties of bulk grain samples are correlated with the bulk density of the samples rather than with true density (Macana and Baik, 2017). Bulk density of dried grains has linear relation to the ε' and ε" (Nelson and Trabelsi, 2012).

During dielectric heating alternating electromagnetic field increases the kinetic energy of the molecules present in samples. These molecules vibrate rapidly, which generate heat causing protein molecules and nucleic acids (DNA and RNA) to denature in the insect bodies and rapid loss in moisture along with disruption of cell membranes causing the cells to lose its microenvironment required for its metabolism, thus the cells die eventually (Bowler and Fuller, 1987). Disinfestation process using dielectric heating largely depends on kinetics of thermal reactions of the vital components in insect pests considering heat tolerance of different insects differ significantly (Wang et al. 2007b). The lethal time (LT) and lethal temperature are dependent on the insect species, development stage, MW or RF power, and moisture content (MC) of grains. Thus, determination of optimum time and temperature combination to kill all life stages of insect pests is important in designing an effective dielectric heating disinfestation protocol (Fakude, 2007). Apart from volumetric heating, different other heating mechanisms are involved during the dielectric heating assisted disinfestation such as conduction between insect bodies and grain particles and convective heat transfer from water vapor generated from wet grains and insect bodies. Therefore, time and temperature combination to kill insects in stored grains differs with insect species and type of grains.

1.4.3.2 Microwave heating application in disinfestation

MW heating is capable of rapidly heating the insects in stored grains with less impact in the environment (Baykal, 2002; Das et al., 2013; Halverson et al., 1998; Ikediala et al., 1999; Nelson, 1996; Karabulut, 2002; Wang and Tang, 2001). Table 1.4 shows some of the combinations of time, temperature, and MW power to obtain 100% mortality of some primary insects at different life stages infesting common stored grains.

Table 1.4: Microwave treatment required to achieve 100% mortality of various insects infesting grains at different moisture contents.

Insect species	Stage	Infesting Grain	Grain moisture	Time (s)	Final temperature	Micro wave	Microw ave frequen	Reference

			content (% wet basis)		of grains (℃)	power (W)	cy (GHz)	
S. zeamais	Larvae and adults	Corn	14, 16, and 18	28	63, 62, and 63	500	2.45	Vadivambal et al 2010
S. zeamais	Larvae and adults	Corn	14, 16, and 18	14	55, 52, and 54	600	2.45	Vadivambal et al 2010
T. castaneum	Larvae and adults	Corn	14, 16, and 18	28	63, 62, and 63	500	2.45	Vadivambal et al 2010
T. castaneum	Larvae and adults	Corn	14, 16, and 18	14	55, 52, and 54	600	2.45	Vadivambal et al 2010
P. interpunctella	Larvae	Corn	14 and 16	28	55 and 56	400	2.45	Vadivambal et al 2010
P. interpunctella	Larvae	Corn	14, 16 and 18	28	63, 62, and 63	500	2.45	Vadivambal et al 2010
P. interpunctella	Larvae	Corn	16 and 18	14	48 and 49	500	2.45	Vadivambal et al 2010
P. interpunctella	Larvae	Corn	14, 16 and 18	14	55, 52, and 54	600	2.45	Vadivambal et al 2010
P. interpunctella	Adult	Corn	14	28	56	400	2.45	Vadivambal et al 2010
P. interpunctella	Adult	Corn	14, 16, and 18	14	49, 48, and 49	500	2.45	Vadivambal et al 2010
C. ferrugineus	Adult	Wheat	14, 16, and 18	56	80 to 86	400	2.45	Vadivambal et al 2007
C. ferrugineus	Adult	Wheat	14, 16, and 18	28	80 to 86	500	2.45	Vadivambal et al 2007
S. granarius	Adult	Wheat	14, 16, and 18	56	-	300	2.45	Vadivambal et al 2007
S. granarius	Adult	Wheat	14, 16, and 18	28	80 to 86	500	2.45	Vadivambal et al 2007

Note: Values in the Grain moisture content column corresponds to the Final grain temperature column. "-" represents no reliable data available.

MW heating can effectively eliminate insects of all life stages (egg, young larva, old larva, pupa, and adult) from stored grains at the optimum MW power and LT (Vadivambal et al., 2008; Purohit et al., 2013). MW heating disinfestation is also effective when combined with cold storage. An MW system with a frequency of 2.45 GHz at different power levels (100 W to 500 W) with a combination of cold storage at under 6°C for different periods (24 h, 48 h, and 72 h) can effectively eliminate different life stages of *O. surinamensis, L. serricorne, P. interpunctella, T. castaneum H.*, and *S. oryzae L.* from stored food grains (Gasemzadeh et al., 2010; Valizadegan et al., 2011; Nasab et al., 2009).

Although MW heating has potential for disinfestation applications in grain industry, MW also has some adverse effects on various quality parameters. Major drawback of MW heating is non-uniform temperature distribution in bulk sample which generate "hot-spot", where the temperature in certain spots is significantly higher than the average temperature in the sample. Hotspots generated during MW heating cause thermal degradation in grains such as reduction in germination rates (Manickavasagan et al., 2007; Das et al., 2013). Also, germination rates of grains decrease with increase in MW (Purohit et al., 2013; Vadivambal et al., 2008). Non-uniformity in temperature distribution is dependent on product composition, where higher fat content improves the temperature distribution uniformity and protein content has the opposite effect (Fakhouri and Ramaswamy, 1993). Geometry, volume, and MC of sample influence the heating pattern along with the MW power, treatment time, and MW system (continuous or intermediate) (Manickavasagan et al., 2006; Oliveira and Franca, 2002). MW heating also degrades bread-making quality of wheat and maize flour (El-Naggar and Mikhaiel, 2011). MW heating also change starch and protein structures, moreover, as treatment time increases viscosity of the flour (Naggar and Mikhaiel, 2011). However, MW heating does not change the quality of fat, fibre, carbohydrates, and ash content of the grains nor the flour yield and loaf volume of sample (Naggar and Mikhaiel, 2011). Thus, analysis and consideration of several effects of MW heating on the physiochemical properties of grains along with the calculation of minimal LT, MW power, and lethal temperature of target insect are crucial in designing an optimum MW disinfestation protocol (Manickavasagan et al., 2006). Also, MW fails to penetrate sample thickness greater than 10.16

cm, so treatment of a huge sample volume is a major challenge in MW heating (Vadivambal, 2009). Thus, MW heating is not advisable to be used alone rather integrate with other unit operations especially to improve uniformity in the temperature distribution throughout the sample, and to increase the efficiency of the disinfestation process (Doty and Baker, 1977; El-Naggar et al., 2011; Velu et al., 2006; Walde et al., 2002).

1.4.3.3 Radio frequency heating application in disinfestation

RF heating also follows the dielectric heating principle except for the fact that RF has higher wavelengths than MW (Figure 1.3), thus large volume samples can be treated. Also, heating rates of insect bodies are significantly higher than that of grains during RF (27.12 MHz) heating compared to MW heating (Shrestha and Baik, 2013). So, lethal temperature of target insects reaches in much shorter time while keeping the grains at relatively lower temperature during RF heating, thus minimizing any adverse effects on physicochemical properties of the grains (Shrestha and Baik, 2013). Frequency of RF waves plays as a crucial factor while designing an RF heating disinfestation protocol. Frequency range from 10 MHz to 100 MHz is ideal for selectively heating of insects, as ε” of the insects (*S. oryzae* (L.), *T. aestivum* (L.)) are 5 times higher than that of the stored grains (wheat) (Nelson, 2005). However, due to allowance by the United States Federal Communications Commission (FCC), application of RF frequencies beyond 13.56 MHz, 27.12 MHz, and 40.68 MHz are not common in bioprocessing industries. At lower frequencies of RF energy complete mortality of insects is achieved at lower temperature of host grains as compared to that of higher frequency RF energy (Nelson, 2005). Table 1.5 shows some of the combinations of time, temperature, and RF power to obtain 100% mortality of some common insects at different life stages infesting common stored grains.

Table 1.5: Radio-frequency treatment required to achieve 100% mortality of various insects infesting grains at different moisture content.

Insect species	Stage	Infesting Grain	Grain moisture content (% wet basis)	Time (s)	Final temperature of grains (°C)	Radio-frequency power (W)	Radio wave Frequency (MHz)	Reference
C. ferrungineus	Adults	Wheat (Sample weight = 27 kg)	12, 15, and 18	354, 326, and 276	70 to 80	7000	27.17	Maccana (2019)
T. castaneum	Adults	Rapeseed (Sample volume = 196.3 cm^3	5, 7, 9, and 11	1080, 720, 390, and 140	80	1500	27.12	Yu et al. (2016)
T. castaneum	Adults	Rapeseed (sample volume = 1766 cm^3)	5, 7, 9, and 11	677, 539, 333, and 218	60	1500	27.12	Yu et al. (2016)
C. maculatus F.	Adults	Lentils (sample weight = 6.4 kg)	6.9	600	60	6000	27	Jiao et al. (2012)
C. maculatus F.	Adults	Chickpea, green peas, and lentils	7	300	60	6000	27	Wang et al. (2010)
S. cerealella	Adults	Rough rice (sample weight > 4 kg	11 and 13.5	300	60	2500	27.17	Lagunas-Solar et al. (2007)
R. dominica	Adults	Rough rice (sample weight > 4 kg	11 and 13.5	1800	60	2500	27.17	Lagunas-Solar et al. (2007)
S. Oryzae (L.),	Mixed immatures	Wheat	-	-	56	-	27	Anglade at al. (1979)
S. granarious	Larvae	Wheat	-	-	58	-	27	Anglade at al. (1979)

S. granarious	Pupae	Wheat	-	-	61	-	27	Anglade at al. (1979)
S. granarious	Adults	Wheat	-	-	55	-	27	Anglade at al. (1979)

Note: "-" represents no reliable data available. Grain moisture content column corresponds to the Time column.

Mortality of insects during RF heating is also dependent on volume, MC, and life stages of the insects. Higher MC (5, 7, 9, and 11% w.b.) of the grains, the higher end temperature (80°C) is required to completely kill adult insects (*T. castaneum*) in stored grains (Yu et al., 2016). Also, larger grain sample volume (small-196.3 cm^3 and large-1766 cm^3) is ideal for disinfestation adult insects using RF heating as end temperature (60°C) of host grain is relatively lower than that of smaller volume (80°C) irrespective of grain MC (Yu et al., 2016). However, volume and MC of grains do not have significant effect on killing larvae (Yu et al., 2016). Disinfestation of different life stages of *T. castaneum* in stored rapeseeds at different MC (5, 7, 9, and 11% w.b.) using an RF heating system (1.5 kW and 27.12 MHz) was proven successful with acceptable thermal degradation of physicochemical qualities seeds when end temperature of the rapeseed was limited to 60˚C (Yu et al., 2016). Also, Macana (2019) have shown that bulk sample of *C. ferrungineus* infested wheats of 27 kg can be effectively disinfested using a 50-ohm RF system at once. RF heating is also proven to be efficient in disinfesting different agricultural commodities similar to food grains such as stored nuts, dried fruits and coffee beans from several insect pest species such as *C. pomonella* (L.), *A. transitella*, *A. ludens*, *H. hampei*, and *C. elephas* (Hau et al., 2014; Pan et al., 2012; Wang et al., 2001a, 2001b, 2007b)

One of the major advantages of RF heating over MW heating is the ability of RF waves to penetrate larger sample volumes with higher efficiency in selective heating compared to MW to effectively kill insects in large quantities of stored grains (Shrestha and Baik, 2013). However, RF heating suffers from non-uniformity in heat distribution throughout the sample, causing generation of hotspots. Temperature distribution in bulk samples during RF heating is associated with geometries, physicochemical properties of the sample, the type of RF heating system, and the type of applicator used (Huang et al., 2018; Yu et al., 2016; Jiao et al., 2015). EM wave distribution during an RF heating process plays an important role in temperature distribution in the sample. Thus, it is important to develop an effective RF heating system that generates uniform EM wave distribution throughout the sample (Huang et al., 2018; Yu et al., 2016; Wang et al., 2008). The uniformity in EM wave distribution during RF heating process of agricultural commodities can be improved by integrating different unit operations along with RF heating. Pieces of literature show that many researchers have used hot air, stirring, tumbling, different angles for the electrodes, and PEI blocks combined with RF heating to improve uniformity index (θ) (Wang et al., 2007a, 2007b; Wang et al., 2010; Jiao et al., 2015). RF heating system equipped with properly designed electrodes with other unit operations such hot air force convection heating, conveyor belt movement, and mixing can successfully kill different life stages of *C. maculatus* (F.), and *S. oryzae* (L.) in stored grains (Jioa et al., 2012; Zhou and Wang, 2016). RF heating treatment can change the geometry along with MC of stored grain, due to the expansion of carbohydrates and proteins present in the grain (Yu et al., 2016). Also, radio frequency heating decreases germination of grains (Yu et al., 2016). However, properly designed RF disinfestation protocol does not cause any significant change protein, water activity, starch content, free fatty acid, ash, fat, starch, hardness, and color of food grains (Zhou and Wang, 2016).

1.4.3.4 Remarks on disinfestation using dielectric heating

Dielectric heating has numerous advantages over other disinfestation processes discussed in this chapter. Disinfestation of insect pests in stored grains using dielectric heating is rapid that and can process large volume samples, especially RF heating. Dielectric heating, however, comes with a challenge of generating hotspots during the process, which causes thermal degradation to the grains. Hot spots can be eliminated by making sure that the EM waves are uniformly distributed throughout the sample during the dielectric heating process. The distribution of EM waves is dependent on several parameters such as geometry and physicochemical properties of the grains, the type of dielectric heating system, and the electrodes being used. Also, the integration of other unit operations improves the uniformity index of EM wave distribution during the dielectric heating process. Thus, with the proper design of a dielectric heating system, it can be used effectively in disinfestation of insect pests in stored grains.

1.5 Conclusions

Non-chemical processes such as ionizing radiation, controlled atmosphere, and dielectric heating are effective in disinfesting insect pests in stored grains. However, they come with specific challenges, that include changes to the physicochemical properties of the grains being treated. These problems can be solved by effectively integrating other unit operations such as forced convection, mixing, and movement. Also, proper designing of crucial components present in disinfestation process is crucial to improve the efficiency of disinfestation process. Non-chemical methods have immense potential in substituting popular chemical processes in disinfestation of insect pests in stored grains.

1.6 Acknowledgment

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1.7 References

Ahmed, M. 2001. Disinfestation of Stored Grains, Pulses, Dried Fruits and Nuts, and Other Dried Foods. In: R. Molins (Ed), *Food Irradiation Principles and Applications* (pp. 77-101). New York: John Wiley & Sons. Inc.

Andreuccetti, D., M. Bini, A. Ignesti, A. Gambetta and R. Olmi. 1994. Microwave destruction of woodworms. *Journal of Microwave Power and Electromagnetic Energy* 29(3):153–160.

Anglade, P., H. Cangardel and F. F. Lessard. 1979. Application des O. E. M. de haute frequence et des micro-ondes a la desinsectisation des denrees stockees. In *Proc. Microwave Power Symp. 1979 Digest* (XIV Symp. Int. sur les Applications Energetiques des Micro-ondes), 67-69. Monaco, 11-15 June.

Annis, P. C. 1987. Towards rational controlled atmosphere dosage schedules—a review of the current knowledge. In: E. J. Donahaye & S. Navarro (Eds), *Proceedings of 4th international working conference on stored products protection* (pp. 128-148). Jerusalem: Maor-Wallach Press.

Banks, H. J. and P. C. Annis. 1990. Comparative advantages of high CO_2 and low O_2 types of controlled atmospheres for grain storage. In *Food preservation by modified atmospheres*, ed. M. Calderon and R. Barkai-Golan. Boca Raton: CRC Press.

Bell, C. H. and S. M. Wilson. 1995. Phosphine tolerance and resistance in *Trogoderma granarium* Everts (Coleoptera: Dermestidae). *Journal of Stored Products Research* 31(3):199–205.

Bhuiya, A. D., M. Ahmed, R. Rezaur, G, Nahar, S. M. S. Huda and S. A. K. M. Hossain. 1991. Radiation disinfestation of pulses, oilseeds and tobacco leaves. In *Insect disinfestation of food and agricultural products by irradiation*, 27-50. Vienna: IAEA.

Bond, E. J. 1984. Manual of fumigation for insect control. Food and Agricultural Organization. FAO Viale delle Terme di Caracalla, 355-402. Rome, Italy.

Bond, E. J. and C. T. Buckland. 1979. Development of resistance of carbon dioxide in the granary weevil. *Journal of Economic Entomology,* 72:770–771.

Brower, J. H. and W. Tilton. 1979. Weight loss of wheat infested with gamma radiated *Sitophilus oryzae* (L.) and *Rhyzopertha dominica* (F.). *Journal of Stored Products Research,* 9(1):37–40.

Canadian grain commission. 2020. https://www.grainscanada.gc.ca/en/grain-quality/manage/identify-an-insect/. (2020/02/02).

Choi, C. and A. Konrad. 1991. Finite Element Modeling of the RF Heating Process. *IEEE Trans Magn,* 27(5):4227–4230.

Cleland, M. R. 2013. Advances in Electron Beam and X-ray Technologies for Food Irradiation. In: *Food Irradiation Research and Technology*, ed. X. Fan and C. H. Sommers, 2nd edition, 9-25. Iowa, USA: Blackwell Publishing and the Institute of Food Technologists.

Collins, P. J., G. J. Daglish, H. Pavic, T. Lambkin, R. Kopittke and B. Bridgeman. 2000. Combating strong resistance to phosphine in stored grain pests in Australia. In *Proceedings of the*

2nd Australian Postharvest Technical Conference, ed. E. J. Wright, H. J. Banks and E. Highley, 102-112. Adelaide, South Australia.

Cornwell, P. B. 1966. The Entomology of Radiation Disinfestation of Grain. London: Pergamon Press.

Das, I., G. Kumar and N. G. Shah. 2013. Microwave Heating as an Alternative Quarantine Method for Disinfestation of Stored Food Grains. *International Journal of Food Science*.

De Carli, M., B. Bresolin, C. P. Z. Noreňa, I. Lorini and I. Brandelli, I. 2010. Efficacy of modified atmosphere packaging to control *Sitophilus* spp. in organic maize grain. *Brazilian Archives of Biology and Technology,* 53:1469–1476.

Department of Primary Industries and Regional Development Government of Western Australia 2018 Updated on 12/6/2012 3:15:25 PM Available online: http://www.padil.gov.au.

Doty, N. C. and C. W. Baker. 1977. Microwave conditioning of hard red spring wheat. I. Effects of wide power range on flour and bread quality. *Cereal Chemistry*, 54:717-727.

El-Naggar, S. M. and A. A. Mikhaiel. 2011. Disinfestation of stored wheat grain and flour using gamma rays and microwave heating. *Journal of Stored Products Research,* 47(3):191-196.

Enu, R. and P. Enu. 2014. Sterilization of grains using ionizing radiation: The case study in Ghana. *European Science Journal*, 10(6):117- 136.

Fakhouri, M. O. and H. S. Ramaswamy. 1993. Temperature uniformity of microwave heated foods as influenced by product type and composition. *Food Research International,* 26(2):89–95.

Fakude, M. P. 2007. Eradication of storage insect pests in maize using microwave energy and the effects of the latter on grain quality. http://upetd.up.ac.za/thesis/available/etd-01292009-131525/unrestricted/dissertation.pdf. (2016/12/29).

Fanslow, G. E., and R. A. Saul. 1971. Drying field corn with microwave power and unheated air. *Journal of Microwave Power*, 6(3): 229-235.

Farkas, J. and C. M. Farkas. 2011. History and future of food irradiation. *Trends in Food Science and Technology,* 22(2-3):121-126.

Finkelman, S., S. Navarro, M. Rindner, R. Dias and A. Azrieli. 2006. Effect of low pressures on the survival of *Trogoderma granarium* (Everts), *Lasioderma serricorne* (F.), and *Oryzaephilus surinamensis* (L.) at 30°C. *Journal of Stored Products Research*, 42(1):23–30.

Finkelman, S., S. Navarro, M. Rindner, R. Dias and A. Azrieli. 2003. Effect of low pressures on the survival of cacao beans insects stored at 18°C. *Journal of Stored Products Research,* 39(4):423–431.

Fiszer, W. 1988. Status Report on Food Irradiation in Poland. Submitted to Fifth Meeting of International Consultative Group on Food Irradiation. Vienna. As reported in Consumer Acceptance of Irradiated Foods by Michelle Marcotte, Nordion International Inc. Ontario, Canada

Fu, Y. C. 2004. Fundamentals and industrial applications of microwave and radio frequency in food processing. In: *Food Processing: Principles and Applications,* ed. J. S. Smith and Y. H. Hui. Iowa City, Iowa, IA: Blackwell.

Gannage, J. 2000. Pesticides and human health. http://www.herbs2000.com/articles/pesticides.htm (2016/12/28).

Gasemzadeh, S., A. Pourmirza, M. Safaralizadeh and M. Maroufpoor. 2010. Effect of microwave radiation and cold storage on *Tribolium castaneum* Herbst (Coleoptera: Tenebrionidae) and *Sitophilus oryzae* L. (Coleoptera: Curculionidae). *Journal of Plant Protection Research,* 50(2): 140-145.

Gunasekaran, S. 1990. Grain drying using continuous and pulse microwave energy. *Drying technology,* 6(3):1039-1047.

Halverson, S. L., R. Plarre, T. S. Bigelow and K. Lieber. 1998. Recent advance in the use of EHF energy for the control of insect in stored products. In *Proceedings of the ASAE Annual International Meeting*. Orlando, Florida, USA: ASAE.

Hamid, M. A. K. and R. J. Boulanger. 1969. A new method for the control of moisture and insect infestations of grain by microwave power. *Journal of Microwave Power,* 4(1):11–18.

Hasan, M. and A. R. Khan. 1998. Control of stored-product pests by irradiation. (1998). *Integrated Pest Management Reviews*, 3(1):15–29.

Hou, L., Ling, B. and S. Wang. 2014. Development of thermal treatment protocol for disinfesting chestnuts using radio frequency energy. *Postharvest Biology and Technology,* 98:65-71.

Huang, Z., F. Marra, J. Subbiah and S. Wang. 2018. Computer simulation for improving radio frequency (RF) heating uniformity of food products: *A review. Critical Reviews in Food Science and Nutrition*, 58(6):1033-1057.

IAEA. 2004. Irradiation as a Phytositary Treatment of Food and Agricultural Commodities. IAEA, Vienna.

Ikediala, J. N., J. Tang, L. G. Neven and S. R. Drake. 1999. Quarantine treatment of cherries using 915 MHz microwaves: temperature mapping, codling moth mortality and fruit quality. *Postharvest Biology and Technology* 16(2):127–131.

Jay, E. G. 1971. Suggested procedures and conditions for using carbon dioxide to control stored-product insects in grain and peanut facilities, 51–46, 6. The United States Department of Agriculture, Agricultural Research Service. Washington, DC.

Jefferies, D. J. 1966. PAPER-IV- Effects of Continuous and Fractionated Doses of Gamma Radiation on the Survival and Fertility of *Sitophilus granarius* (L.). *The Èntomol of Radiat Disinfest of Grain*.

Jiao, S., Y. Deng, Y. Zhong, D. Wang and Y. Zhao. 2015. Investigation of radio frequency heating uniformity of wheat kernels by using the developed computer simulation model. *Food Research International*, 71:41–49.

Jiao, S., J. A. Johnson, J. Tang and S. Wang. 2012. Industrial-scale radio frequency treatments for insect control in lentils. *Journal of Stored Products Research,* 48:143-148.

Karabulut, O. A. and N. Baykal. 2002. Evaluation of the use of microwave power for the control of postharvest diseases of peaches. *Postharvest Biology and Technology*, 26(2):237-240.

Kashi, K. P. 1982. Relationship between the level of carbon dioxide in the environment and respiration of some stored-product insects. In *Proceedings of the First Australian Stored Grain Pest Control Conference*, ed. P. Williams and T. G. Amos. Victoria, Melbourne.

Klaseen, W. 2005. Area-Wide Integrated Pest Management and the Sterile Insect Technique. In V. A. Dyck, J. Hendrichs, & A. S. Robinson (Eds), *Sterile Insect Technique Principles and Practice in Area-Wide Integrated Pest Management* (pp. 39-68). Vienna: IAEA.

Kume, T., M. Furuta, S. Todoriki, N. Uenoyama and Y. Kobayashi. 2009. Status of food irradiation in the world. *Radiation Physics and Chemistry*, 78:222-226.

Lagunas-Solar, M. C., Z. Pan, N. X. Zeng, T. D. Truong, R. Khir and K. S. P. Amaratunga, K. 2007. Application of radiofrequency power for non-chemical disinfestation of rough rice with full retention of quality attributes. *Applied Engineering in Agriculture,* 23(5):647-654.

Langlinais, S. J. 1989. Economics of microwave treated rice for controlling weevils. ASAE Paper No 893544. St Joseph, Mich, USA.

Leesch, J. G., G. F. Knapp and B. E. Mackey. 2000. Methyl bromide adsorption on activated carbon to control emissions from commodity fumigations. *Journal of Stored Products Research,* 36(1):65-74.

Macana, R. J. 2018. Disinfestation of rusty grain beetle (*Cryptolestes Ferrungineus*) in stored wheat grain using 50-ohm radio frequency (RF) heating system, Published MSc thesis. Department of Chemical and Biological Engineering, University of Saskatchewan.

Macana, R. J. and O. D. Baik. 2017. Disinfestation of insect pests in stored agricultural materials using microwave and radio frequency heating: A review. *Food Review Internationals*, 34(5):483-510.

Manickavasagan, A., D. S. Jayas and N. D. S. White. 2006. Non uniformity of surface temperatures of grain after microwave treatment in an industrial microwave dryer. *Drying Technology*, 24(12): 1559-1567.

Marzke, F. O., A. F. Press Jr and G. C. Pearman Jr. 1970. Mortality of rice weevil, Indian-meal moth and *Trogodrema glabrum* exposed to mixtures of atmospheric gases at various temperatures. *Journal of Economic Entomology*, 63(2):570-574.

Mbata, G. N., M. Johnson, T. W. Phillips and M. Payton. 2005. Mortality of life stages of cowpea weevil (Coleoptera: Bruchidae) exposed to low pressure at different temperatures. *Journal of Economic Entomology*, 98(3):1070-1075.

Mitcham, E. J., R. H. Veltman, X. Feng, E. de Castro, J. A. Johnson, T. L. Simpson, W. V. Biasi, S. Wang and J. Tang. 2004. Application of radio frequency treatments to control insects in in-shell walnuts. *Postharvest Biology and Technology*, 33(1):93–100.

My NASA Data. 2018. https://mynasadata.larc.nasa.gov/science-practices/electromagnetic-diagram/ (2018/06/06).

Nasab, F. S., A. A. Pourmirza and A. H. Zade. 2009. The effect of microwave radiation with cold storage on the mortality of Indian meal moth (*Plodia Interpunctella* Hub.) Eggs. *Pakistan Journal of Entomology*, 31(2):111-115.

Navarro, S. 2012. The use of modified and controlled atmospheres for the disinfestation of stored products. *Journal of Pest Science*, 85:301–322.

Navarro, S. and M. Calderon. 1979. Mode of action of low atmospheric pressures on *Ephestia cautella* (Wlk.) pupae. *Experientia*, 35(5):620-621.

Nelson, S. O. 1996. Review and assessment of radiofrequency and microwave energy for stored-grain insect control. *Transactions of the ASAE*, 39(4):1475-1484.

Nelson, S. O. 2005. Dielectric spectroscopy in agriculture. *Journal of Non-Crystalline Solids*, 351:2940-2944.

Nelson, S. O. 2004. RF and microwave permittivities of insects and some applications. In: URSI EMTS international symposium on electromagnetic theory. In *URSI EMTS International Symposium on Electromagnetic Theory*, 1224-1226. Pisa, Italy. May 23-27.

Nelson, S. O. and J. A. Payne. 1982. RF dielectric heating for pecan weevil control. *Transactions of the ASAE* 25(2):0456-0458.

Nelson, S. O. and S. Trabelsi. 2012. Factors Influencing the Dielectric Properties of Agricultural and Food Products. *Journal of Microwave Power Electromagnetic Energy*, 46(2):93-107.

Njoroge, A. W., H. D. Affognon, C. M. Mutungi, J. Manono, P. O. Lamuka and L. L. Murdock. 2014. Triple bag hermetic storage delivers a lethal punch to *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae) in stored maize. *Journal of Stored Products Research*, 58:12-19.

Oliveira, M. E. C. and A. S. Franca. 2002. Microwave heating of foodstuffs. *Journal of Food Engineering*, 53(4):347–359.

Pan, L., S. Jiao, L. Gautz, K. Tu and S. Wang. 2012. Coffee bean heating uniformity and quality as influenced by radio frequency treatments for postharvest disinfestations. *Tansactions of the American Society of Agricultural and Biological Engineers*, 55:2293-2300.

Purohita, P., D. S. Jayasa, B. K. Yadav, V. Chelladuraia, P. G. Fields and N. D. G. White. 2013. Microwaves to control *Callosobruchus maculatus* in stored mung bean (*Vigna radiata*). *Journal of Stored Products Research,* 53:19-22.

Riganakos, K. A. 2010. Irradiation of Food Commodities. In *Food Irradiation techniques*, 23-42.

Riudavets, J., C. Castañé, O. Alomar, M. J. Pons and R. Gabarra. 2009. Modified atmosphere packaging (MAP) as an alternative measure for controlling ten pests that attack processed food products. *Journal of Stored Products Research*, 45(2):91-96.

Rohitha, B. D. P., R. F. Hafeel, K. M. S. Wimalasiria and U. P. D. Pathirana. 2014. End-use quality characteristics of hermetically stored paddy. *Journal of Stored Products Research*, 59:158-166.

Shrestha, B. and O. D. Baik. 2013. Radio frequency selective heating of stored-grain insects at 27.12 MHz: A feasibility study. *Biosystems Engineering*, 114(3):195-204.

Siddhuraju, P., P. S. Makkar and K. Becker. 2002. The effect of ionising radiation on antinutritional factors and the nutritional value of plant materials with reference to human and animal food. *Food Chemistry*, 78(2):187-205.

Singh, B. and P. S. Datta. 2010. Effect of low dose gamma irradiation on plant and grain nutrition of wheat. *Radiation Physics and Chemistry*, 79(8):819-825.

Sinha, R. N. and F. L. Watters. 1985. Insect pests of flour mills, grain elevators, and feed mills and their control. Agriculture Canada 1985(1776), 290. Winnipeg, Manitoba, Canada.

Stratton, J. A. 2007. Electromagnetic Theory. New York, USA: John Wiley and Sons.

Subramanyam, B. H. and D. Hagstrum. 1995. Resistance measurement and management. In: *Integrated Management of Insects in Stored Products*, ed. B. H. Subramanyam and D. Hagstrum. New York, USA: Marcel Dekker Inc.

Tilton, E. W. and J. H. Brower. 1983. Radiation effects on arthropods. In: *Preservation of food by ionizing radiation,* ed. E. S. Josephson and M. S. Peterson, 2:269-316. Boca Raton, FL: CRC Press Inc.

UNEP (United Nations Environment Programme). 1997. Report of the 9th Meeting of the parties to the Montreal protocol on substances that deplete the ozone layer. Montreal. Canada: UNEP/OzL.Pro. 1997/09/12.

USDA (United States Department of Agriculture). 2015. Stored Grain Insects. Federal Grain Inspection Service United States Department of Agriculture. doi: https://www.gipsa.usda.gov/fgis/.../ref/Stored%20Grain%20Insects_2015-03-04.pdf

Vadivambal, R., O. F. Deji, D. S. Jayas and N. D. G. White. 2010. Disinfestation of stored corn using microwave energy. *Agriculture and Biology Journal of North America*, 1(1):18-26.

Vadivambal, R. 2009. Disinfestation of Stored Grain Insects Using Microwave Energy Published Ph D thesis. Department of Biosystems Engineering, University of Manitoba.

Vadivambal, R., D. S. Jayas and N. D. G. White. 2008. Mortality of stored-grain insects exposed to microwave energy. *Transactions of the ASABE*, 51(2):641–647.

Valizadegan, O., A. A. Pourmirza and M. H. Safaralizadeh. 2011. The impact of microwaves irradiation and temperature manipulation for control of stored-products insects. *African Journal of Biotechnology*, 10(61):13256-13262.

Velu, V., A. Nagender, P. G. P. Rao and D. G. Rao. 2006. Dry milling characteristics of microwave dried maize grains (*Zea mays* L.). *Journal of Food Engineering*, 74(1):30-36.

Von Hippel, A. R. 1954. Dielectric Properties and Waves. New York, USA: John Wiley.

Wang, S. and J. Tang. 2001b. Radio frequency and microwave alternative treatments for insect control in nuts: A review. *Agricultural Engineering Journal*, 10(3&4):105-120.

Wang, S., J. N. Ikediala, J. Tang and J. D. Hansen. 2002a. Thermal death kinetics and heating rate effects for fifth instar *Cydia pomonella* (L.) (Lepidoptera: Tortricidae). *Journal of Stored Products Research*, 38(5):441-453.

Wang, S., M. Monzon, J. A. Johnson, E. J. Mitcham and J. Tang. 2007a. Industrial-scale radio frequency treatments for insect control in walnuts. I: Heating uniformity and energy efficiency. *Postharvest Biology and Technology*, 45(2):240–246.

Wang, S., M. Monzon, J. A. Johnson, E. J. Mitcham and J. Tang. 2007b. Industrial-scale radio frequency treatments for insect control in walnuts. II: Insect mortality and product quality. *Postharvest Biology and Technology*, 45(2):247–253.

Wang, S., J. Tang and R. P. Cavalieri. 2001a. Modeling fruit internal heating rates for hot air and hot water treatments. *Postharvest Biology and Technology*, 22(3):257–270.

Wang, S., J. Tang, J. A. Johnson and J. D. Hansen. 2002b. Thermal death kinetics of fifth instar *Amyelois transitella* (Walker) (Lepidoptera: Pyralidae). *Journal of Stored Products Research*, 38(5):427-440.

Wang, S., J. Tang, J. A. Johnson, E. Mitcham, J. D. Hansen, R. P. Cavalieri, J. Bower and B. Biasi. 2002c. Process protocols based on radio frequency energy to control field and storage pests in shell walnuts. *Postharvest Biology Technology*, 26(3):265–273.

Wang, S., G. Tiwari, S. Jiao, J. A. Johnson and J. Tang. 2010. Developing postharvest disinfestation treatments for legumes using radio frequency energy. *Biosystems Engineering*, 105(3):341-349.

Wang, S., J. Yue, B. Chen and J. Tang. 2008. Treatment design of radio frequency heating based on insect control and product quality. *Postharvest Biology Technology*, 49:417–423.

Wang, Y., Y. Li, S. Wang, L. Zhang, M. Gao and J. Tang. 2011. Review of Dielectric Drying of Foods and Agricultural Products. *International Journal of Agricultural and Biological Engineering*, 4(1):1–19.

Watters, F. L. 1976. Microwave radiation for control of *Tribolium confusum* in wheat and flour. *Journal of Stored Products Research*, 12(1):19–25.

Watters, F. L. and K. F. MacQueen. 1967. Effectiveness of gamma irradiation for control of five species of stored-product insects. *Journal of Stored Products Research*, 3:223–234.

WHO. 1994. Safety and nutritional adequacy of irradiated food. Geneva: WHO.

Yang, T. C. H., I. L. Silver and B. Heinze. 1970. Development studies of X-irradiated *Tribolium confusum* eggs. *Tribolium Information Bulletin*, 13:90–93.

Yu, D., B. Shrestha and O. D. Baik. 2016. Radio frequency (RF) control of red flour beetle (*Tribolium castaneum*) in stored rapeseeds (*Brassica napus* L.). *Biosystems Engineering*, 151:248-260.

Zhou, L. and S. Wang. 2016. Verification of radio frequency heating uniformity and *Sitophilus oryzae* control in rough, brown, and milled rice. *Journal of Stored Products Research*, 65:40-47.

CHAPTER 2

Characterization of 50-ohm radio frequency heating and the effect of heating on the quality of bulk *Brassica napus*. L seeds

Contribution of this chapter on overall study

Characterization of 50-ohm radio frequency heating of bulk canola seeds in a tubular applicator with parallel electrodes plays an important role in this research. This chapter describes the temperature distribution of bulk canola during the RF heating process at different power level. The generation of hot, and cold spots during the RF heating process helped to record the temperature histories at various points in the bulk canola seeds. These temperature histories were then used to design various time, and temperature based linear regression models, which were used in developing death kinetics model of the adult red flour beetles infesting the canola seeds. Also, the post-treatment qualities of the canola seeds were analysed, which helped determined the lethal temperatures to kill the insects without altering the physicochemical properties of the canola seeds.

2.1 Abstract

A pilot-scale 50-ohm radio frequency (RF) heating system was used to determine the temperature distribution of bulk canola seeds (*Brassica napus* L.), 9% moisture content (MC) wet-basis (w.b.) in a tubular applicator with parallel electrodes. Non-uniformity of the temperature distribution of

bulk canola was observed during the RF heating process of the seeds. The hottest spot was observed at the front side of the tubular cavity of the applicator adjacent to the hot electrode. The average temperature (T_{avg}) of the canola seeds was 38.00±0.62℃, 42.20±0.28℃, and 40.00±0.35℃ at 3 kW, 5 kW, and 7 kW respectively. Temperature distribution was relatively uniform in the back zone (0.287, 0.433, and 0.278 for 3 kW, 5 kW, and 7 kW respectively). The physicochemical properties of canola seeds changed significantly after 50-ohm RF heating at various end temperatures and power levels.

2.2 Industrial relevance text

Radio frequency heating is an emerging technology and has immense potential in food grains, pulses, and oilseeds processing. The radio frequency heating can be used for disinfestation of insects, drying, and removal of anti-nutritional compounds in stored food grains, pulses, and oilseeds. Radio frequency heating is based on dielectric heating principle thus allowing selective and volumetric heating. The radio frequency waves have wavelengths ranging from 1 mm to about 100 km with a frequency of 3 kHz to about 300 GHz, the penetration depth is comparatively higher than microwaves, which has wavelengths ranging from 1mm to about 1 m with frequencies between 300 MHz and 300 GHz. Thus, radio waves penetrate larger volume objects compared to microwaves. This research investigated a 50-ohm radio frequency heating system with a through field parallel plate type applicator to observe the temperature distribution throughout the bulk canola at different power levels. Understanding the characteristics of 50-ohm radio frequency heating of bulk canola seeds at different power levels can help design effective heating processes involved in canola seeds storage and handling.

2.3 Nomenclature

ANOVA analysis of variance

AV p-anisidine value

EM electromagnetic

FCC Federal Communications Commission

h height (m)

l length (m)

MC moisture content (%)

MW microwave

PV peroxide value

RF radio frequency

RFG radio frequency generator

RH relative humidity (%)

T temperature (°C)

t time (s)

T_{avg} average temperature (°C)

TOTOX total oxidation

w.b. wet basis

θ uniformity index

λ wavelengths (m)

2.4 Introduction

Radio frequency (RF) heating is based on the interactions between high frequency electromagnetic (EM) waves and commodities containing polar molecules and ions. Radio waves range from 1 mm to about 100 km with frequency of 3 kHz to about 300 GHz (NASA, 2020), however, United States Federal Communications Commission (FCC) allows the use of only 13.56 MHz, 27.12 MHz, and 40.68 MHz for RF heating applications in industrial, scientific, and medical (ISM) sectors, to avoid disturbances in communication system (Wang et al., 2011). RF heating is governed by the characteristics of EM energy, and by the electrical, thermal, and physical properties of the material. A substantial advantage of RF heating is selective heating, materials with higher dielectric loss factor heat up at a much faster rate than those with lower dielectric loss factor (Shrestha and Baik, 2013a; Yu et al., 2015). In recent times, the use of RH heating has become a popular choice in agricultural products and food processing, e.g. disinfestation of insect pests in stored grains and oilseeds, meat thawing, drying of agricultural commodities. There are two types of RF systems, through which the radio waves are generated and transmitted to the material being processed; free-running oscillator type or the conventional type and 50-ohm type (Marra et al., 2009). The free oscillator type RF system consists of an RF generator (RFG) through which oscillating EM waves and transmitted to the material through the electrodes (anode and ground electrode). The 50-ohm system comprises of an RFG that generates the RF energy and the RF energy is transferred to a matching network through a 50-ohm cable. The matching network is connected to the electrodes through which the radio waves are generated and transferred to the materials being processed. The 50 ohm RF system is relatively new comparing to the conventional one, although, the conventional RF system is the popular one in the industries, the 50 ohm RF system is capable of producing constant frequency, and power as the matching network automatically adjusts to maintain the load impedance (Jones, and Rowley, 1996). The RFG is connected to the matching network with a standard 50-ohm cable, and the RFG can be located remotely, giving the advantage of flexibility in the design of the RF heating system.

One of the major drawbacks of an RF heating system is a non-uniform distribution of temperature in the sample and the non-uniformity in the temperature distribution is unique in every RF system (Yu et al., 2016a). Thus, the characterization of the heating pattern of any sample in an RF heating system is crucial to design appropriate sample handling mechanisms (applicator) to improve uniformity in heating substances. The design of the RF applicator is defined by the RF application, thus, the shape and size of the applicator widely vary from one another, and an RF applicator can be classified as: through field type, fringe field type, and staggered through field type (Jones and Rowley, 1996). Amongst the three types of RF applicators, the through field type is the most popular one with the simplest construction, the applicator consists of parallel plates electrodes (anode and ground), in between the electrodes the sample is introduced to form a parallel capacitor. This type of applicator can heat up larger bulk materials, thus, making it an ideal candidate for large volume sample treatment. The RF heating mechanism in parallel plate type applicator includes introduction of high voltage in the anode electrode while the other electrode is grounded thus forming propagation of EM waves in between the electrode and causing dielectric heating characteristics in the sample (Huang et al., 2018). Due to the dielectric heating characteristics, RF heating is expected to have a more uniform heating pattern compared to the other heating methods including MW heating. Luechapattanaporn et al. (2004) concluded that, the difference in wavelengths makes RF heating more suitable in heating a sample filled in a polymeric tray (245 × 235 × 45 mm), by providing more uniformity in temperature distribution. Explaining that radio waves wavelengths (λ) are greater than that of MW, thus providing higher penetration depth in RF heating (Luechapattanaporn et al. 2004).

Literature shows non-uniformity in temperature distribution in various agricultural commodities such as fresh apples, canola seeds, and chestnuts during RF heating (Birla et al. 2008b; Yu et al., 2016a; Hou et al., 2014). Temperature uniformity (θ) in RF heating is affected by several parameters including thermal, physical, and electrical properties of the sample, along with the size, shape, and location of the sample in the RF applicator (Yu et al., 2016a). Romano and Marra (2008) simulated the temperature distribution in meat and the effect of different shapes of samples (cube, cylinder, and sphere) on the temperature distribution and found that meat cut in cubical shapes had less temperature variation than meat cut in the other shapes. Tiwari, Wang, Tang, and Birla (2011a) simulated the heating pattern in wheat flour samples in three differently shaped containers (cuboid, ellipsoid, and cylinder). They reported that the higher power densities were found in the center parts of the ellipsoid and at the edges of the other shapes.

Several researchers used gel samples of different shapes and sizes and exposed to RF heating and studied the temperature distribution in chemically and structurally homogenous objects and found out that temperature distribution was mainly dependent of the electric field distribution inside the objects (Yang and Gunasekaran 2001; Birla et al. 2008a; Yu et al. 2016a). Yu et al. (2016a) studied the temperature distribution during RF heating (1.5 kW and 27.12 MHz) of a packed bed of canola seeds at different MCs and volumes. Their sample container was infinite cylindrical, of which the bottom surface sits on the ground electrode of two parallel electrodes. They encountered edge effect during heating packed-bed canola seeds at different MCs and volumes. The concentration of electric field at outer edges of the material due to the deflection of electric fields at the edge and the corners of the material's container caused the edge effect. They further suggested their work lay a foundation for designing and simulating an RF heating system/process that can achieve more uniform heating of bulk canola seeds.

Canola happens to be one of the most important oilseed crops in the world of agriculture. China, India, Canada, and European Union are the top producers of the crop, total world production in 2018 - 2019 was 72.80 million metric tons and in 2019-2020 is expected to be 74.80 million metric tons (USDA Foreign Agricultural Service, 2019). Canada exports over 90% of the canola produced around the world. Such an essential crop in the economy of Canada, canola does face some significant challenges in production, around 8 to 10% in annual crop yield is lost due to insect pest causing hundreds of millions of dollars lost in the Canadian economy (Canola Watch 2015). Thus, proving the importance of the development of quick and effective disinfestation process and RF heating has the potential to solve the problem. Thus, the focus of this chapter is to examine temperature distribution in a packed bed of canola seeds (*Brassica napus* L.) during 50-ohm RF heating at various power levels. By doing so, the heating characteristics of bulk canola seeds using a 50-ohm RF heating with parallel plate type applicator can be understood, thus helping in effective utilization of RF heating for the disinfestation of insects in stored canola. As, along with economic losses, insect pest infestation is a considerable barrier to export and constitutes a significant concern in the production, storage, and the process of all food products (Gao et al., 2010). The trade regulations of domestic and international markets have required postharvest treatments of all food products to ensure quarantine security from insect pests (Birla et al. 2008; Jiao et al. 2011).

The Engineering Shop at the University of Saskatchewan fabricated the tubular applicator with parallel plate electrodes where the applicator was connected to a matching network and 15 kW 27.12 MHz RFG which is relatively a new RF heating system configuration. Literature shows limited application of 50-ohm RF heating of oilseeds, thus, the characterization of the heating pattern of the bulked canola seeds using the RF heating system plays an important role to understand the heating characteristics considering affecting parameters. Doing so will show several drawbacks in the design and considerations in manufacturing the 50-ohm RF heating system. Thus, to improve the design of the sample handling mechanisms (applicator) to improve uniformity in heating substances, this chapter focuses on examining temperature distribution in a packed-bed of canola seeds in a tubular cavity between two parallel electrodes during 50-ohm RF heating at various power levels. This applicator design was to house auger screws and very rare in RF heating applications. Along with the heating distribution, we have also examined θ of canola seeds using a 50-ohm RF system at 3 kW, 5 kW, and 7 kW. Also, this chapter shows the comparison of physicochemical properties of canola seeds before and after the RF treatment that resulted in 100% mortality of insect pests, which include MC, germination rate, colour, and oil quality before and after the RF treatment.

2.5 Materials and methods

2.5.1 The radio frequency system

The Engineering Shop at the University of Saskatchewan fabricated the tubular applicator with parallel plate electrodes based on our design, and the applicator was connected to a matching network and 15 kW 27.12 MHz RFG manufactured by Coaxial Power System Ltd (Figure 2.1).

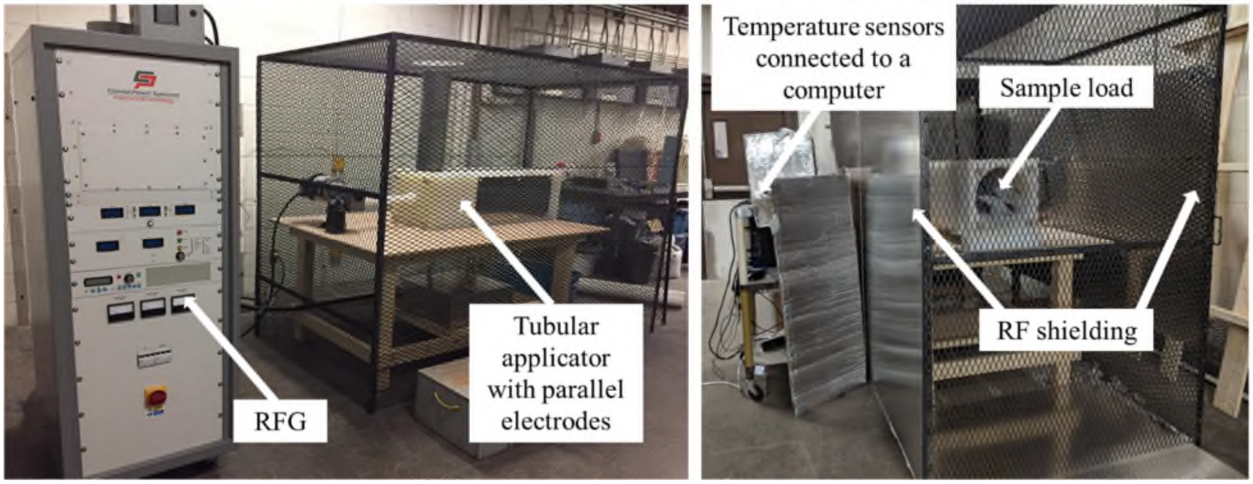


Figure 2.1: 50-ohm radio frequency heating system set-up (actual).

2.5.2 Radio frequency generator

According to Coaxial Power System Ltd., the RFG was designed to drive a specific characteristic impedance, 50-ohm. As described by Coaxial Power System Ltd. (2016), the characteristic impedance of the output cable allows the RFG to deliver full power at maximum efficiency. If the output impedance varied from 50-ohm the protection circuits in the RFG reduce the output power in order to protect the RFG from overload. Except for dummy loads and some types of antenna most real-world loads differed substantially from 50-ohm and the system needs a device to transform the output of the RFG to the actual load impedance. It was sometimes possible to use a conventional wound transformer, but most often the matching device was made up of a network of series and parallel impedances that combine to perform the transformation, i.e. a 'Matching Network'.

Figure 2.2: Radio frequency generator (Coaxial Power Systems Ltd.).

2.5.3 Representing radio frequency impedances

The impedance of an application is rarely pure resistance; often, it consists of a combination of resistance and capacitance. An 'equivalent circuit' can be considered to consist of a resistor and a capacitor. Two forms of circuit exist, series and parallel, neither form is correct or incorrect, both have validity, nor it is possible to represent the output in whichever form is most convenient. The Parallel form represents a load as a resistor and a capacitor in parallel. The resistor would typically be high in value and convenient when considering the 'PI' network, as the tuning capacitor adds to the parallel equivalent capacitance. The Series form represented a load like a resistor and a capacitor in series. The resistor would typically be low in value, convenient when considering the 'L' network as the tuning capacitor appears in series with the series equivalent capacitance. In the case of the 'T' the inductor, leaving just enough inductance to allow it to tune in, resonates network the series capacitance out.

2.5.4 Matching network

Coaxial Power Systems Ltd manufactures two styles of impedance matching network to link the load to the RFG. The matching network adjusts the input impedance of the load to 50-ohms to

Figure 2.3: Automatic matching network (Coaxial Power Systems Ltd.).

transfer maximum power from the RFG, whose output impedance is 50-ohms, to the load. The network was installed as close as possible to the load. The best possible position, in our RF heating application, for example, the network was mounted directly on the heating applicator with a direct connection to the electrode.

2.5.5 Applicator

The applicator used in this research was a parallel plate type electrodes (hot and ground). The parallel plate electrodes are connected to the matching network in the back end of the setup as shown in Figure 2.1. The connection was made with the assumption that the electric field strengths are uniform from beginning to the end of the electrode. In between the two electrodes was the tubular channel, made of polypropylene composite; diameter of 30 cm and length of 70 cm. The gap size between the two electrodes was 36 cm as shown in Figure 2.4. The samples consisting of insects and canola grains were loaded in the channel which acted as an insulator during the RF heating process, where, the insects were killed and the canola grains being heated. This study used an applicator with parallel plate electrodes because of its uniform electric field strengths from beginning to end of the electrode. The layout of the RF system is shown in Figure 2.4.

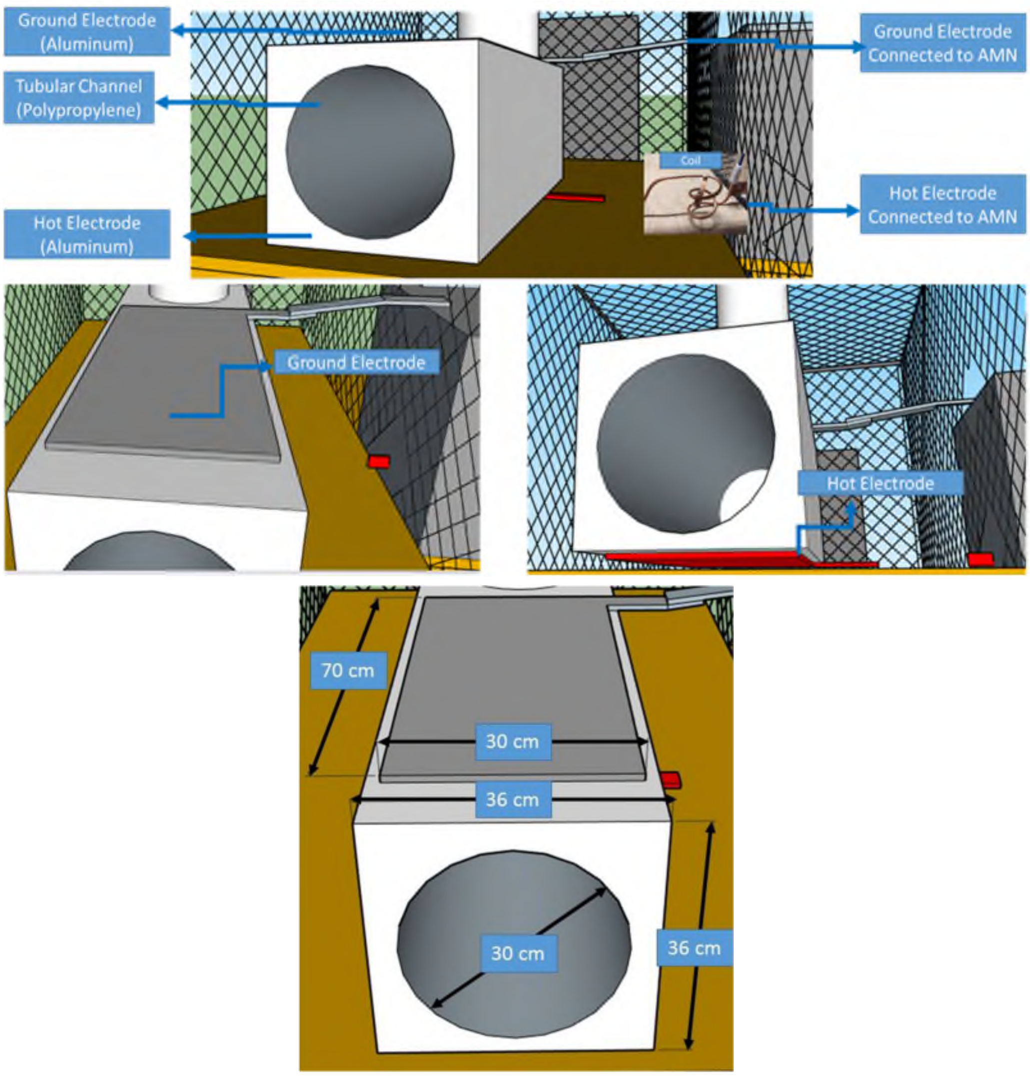


Figure 2.4: 50-ohm radio frequency applicator (hot electrode and cold electrode).

2.5.6 Canola seeds

9% MC (w.b.) canola samples from various MC levels (6, 7, and 9%) bulk canola were prepared from seed samples provided by Viterra Inc. The seeds were cleaned using a grain cleaning system and transported in polypropylene containers and are stored in cold storage for a maximum period of 6 months at 4°C before using them. To determine the MC of the canola samples 10 g of canola seeds were dried for 24 h at 103°C in three replicates a hot air oven (Despatch, Despatch Industries, MN, USA) (ASAE, 2002; Brusewitz, 1975). 9% MC canola seeds were prepared by spraying a pre-calculated amount of distilled water on the known mass of the seeds at initial MC contained in a polypropylene container. The polypropylene containers were agitated by continuously shaking and rotating while spraying distilled water. The containers were left at room temperature (24°C) for three days with periodic shaking, after three days the MC was measured, and the process was repeated to achieve an equilibrium MC of 9% MC, then it was followed by storing them at the cold storage (4°C) until used. A digital scale with an accuracy of ±0.01 g (Symmetry, PR4200, Cole-Parmer Instrument Co., IL, USA) was used for all weighing and left the samples at room temperature for 24 hours and measured the final MC of samples before using them for experiments (allowing ±0.2% error).

2.5.7 Experimental setup of heating distribution in bulk canola bed using radio frequency heating

27 kg of canola seeds were packed tightly in 7 polypropylene bags to fill a tubular cavity of 70 cm in length and 30 cm in diameter (Figure 2.5). In the process, it was made sure that the bags are packed tightly and uniformly by dividing the weight equally.

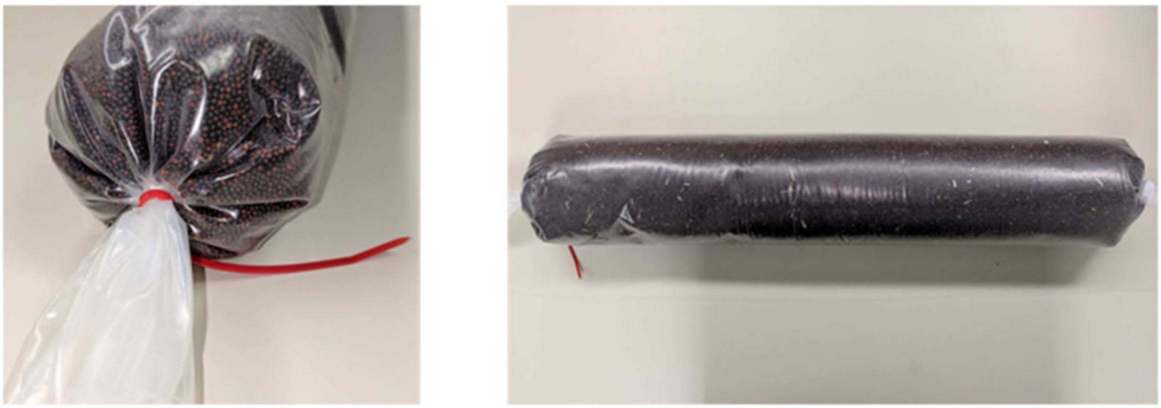


Figure 2.5: Canola seeds in polypropylene bags.

Three optic fibre temperature sensors were inserted in each bag; 1^{st} location 5 cm from the end, 2^{nd} location 30 cm from 1^{st} location and 3^{rd} location 30 cm from 2^{nd} location as shown in Figure 2.6.

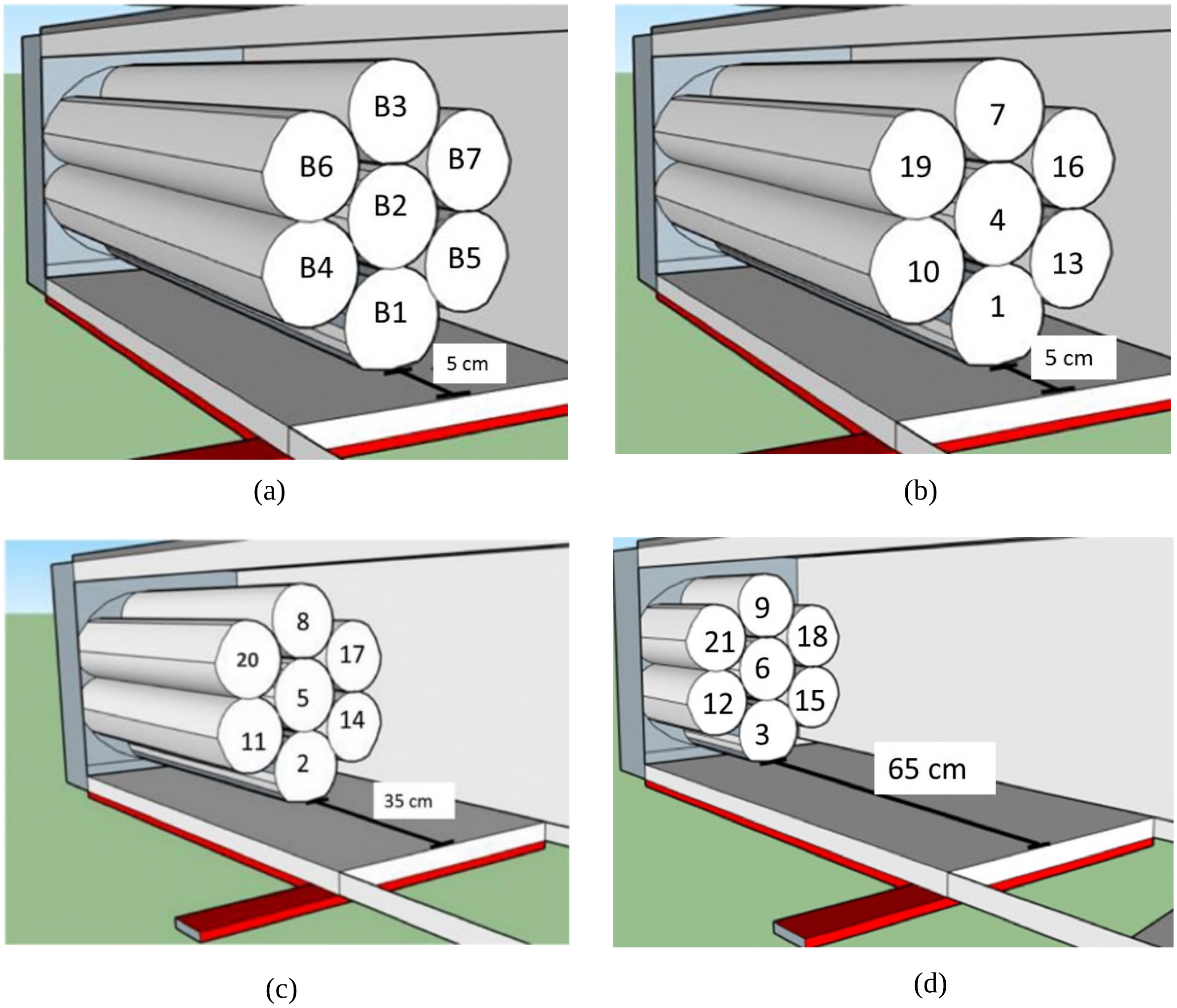


Figure 2.6: (a) Bag numbers (b) Cross sectional view of canola bags setup in the applicator along with location number at front zone (c) Cross sectional view of canola bags setup in the applicator along with location number at middle zone (d) Cross sectional view of canola bags setup in the applicator along with location number at back zone.

The locations were numbered as followed:

- 1, 2 and 3 in bag 1 (B1)
- 4, 5 and 6 in bag 2 (B2)
- 7, 8 and 9 in bag 3 (B3)

- 10, 11 and 12 in bag 4 (B4)
- 13, 14 and 15 in bag 5 (B5)
- 16, 17 and 18 in bag 6 (B6)
- 19, 20 and 21 in bag 7 (B7)

A Reflex™ signal conditioner and the fiber optic temperature sensors with an accuracy of ±0.8°C (Neoptix, Québec City, Québec, Canada) were used to measure and monitor the temperatures of samples. The temperature probes were inserted exactly 5 cm low; we recorded the temperatures histories at 3 kW, 5 kW, and 7 kW. The temperature probes had a response time of 0.25 s (stagnant air) which requires to reach 63% of the actual value (Neoptix, Québec City, Québec, Canada). A LabVIEW (2010v.10) program was developed to interface with the data acquisition device connected to the temperature sensors. The temperatures of the sample were displayed and recorded every 2 s. All the experiments were triplicated and the average of three repetitions are reported.

2.5.8 Uniformity index of canola seeds

The horizontal and vertical uniformity index (θ) of the bulk canola seeds with 50-ohm RF heating were estimated. Equation (2.1) and (2.2) (Neter, Kutner, Wasserman, & Nachtsheim, 1996) describe variation in the mean and standard deviation of the sample:

$$\Delta\mu = \mu_t + \mu_0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (2.1)$$

$$\Delta\sigma = \sqrt{(\sigma_t^2} - \sigma_0^2) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.2)$$

Where, μ and σ represent the temperatures' mean and standard deviation respectively, and Δ is the increment. The subscripts 0 and t denote the temperatures at initial heating and after t seconds of RF heating respectively.

The θ can then be obtained by combining Equation (2.1) and (2.2), and shown in Equation (2.3) (Gao, Tang, Wang, Powers, & Wang, 2010):

$$\theta = \frac{\Delta\sigma}{\Delta\mu} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.. (2.3)$$

A small value θ is necessary for a well-designed RF heating system and slow increments in the standard deviation of the temperature as the mean temperature rises.

2.5.9 Seed quality analysis

Seed quality analysis included a comparison of MC, germination rate, colour change and oil quality of canola seeds before and after RF heating at various end temperatures and various power levels. For the canola seed quality analysis, the seeds from the hottest spot of the bulk seeds were considered. The seeds at the hottest spot (Location 1) were heated to end temperatures of 50°C, 55°C, 60°C, and 65°C from 24°C. After the seed temperature reaches 50°C, 55°C, 60°C, and 65°C from 24°C, the RF heating was stopped instantly as soon as the temperature at location 1 reaches the end temperature. The temperature was monitored in real-time using a Reflex™ signal conditioner and a fiber optic temperature sensor (Neoptix, Québec City, Québec, Canada). The fiber optic temperature was inserted vertically 5 cm deep from the horizontal upper surface of the canola bag at Location 1. The RF treated canola seeds were collected from the surrounding of Location 1 (B1), all the samples from 0 cm to 10 cm in the front zone of B1 were collected. The samples were quickly cooled down to room temperature (22°C) and sealed in Ziploc® bags and stored in cold storage at 4°C, and the seed qualities were analyzed the following day. This set of temperatures was chosen because thermal degradation of canola seeds using RF heating starts at around 60°C (Yu et al. 2016b).

2.5.9.1 Moisture content

The MC of the canola seeds were measured using ASAE (2000), 10 g of canola seeds samples were measured using a weighing balance, TS200S Ohaus Corporation, USA (maximum load capacity = 200 g, and readability = 0.001 g) and poured onto an aluminum moisture dish (10 mm diameter), the aluminum moisture dishes were placed in a hot air oven (Despatch, Despatch Industries, MN, USA) for 24 h at 103°C. The MC of the canola seeds were then determined based on the change of weight of the seeds before and after the oven drying process.

2.5.9.2 Germination test

A total of 10 RF treated canola seeds were placed on one Whatman # 3 filter papers with 5 ml of distilled water in a 90 mm-diameter plastic petri dish. The seed samples were kept in a Ziploc® bag to prevent moisture loss. It was then subjected to germination in a temperature and humidity chamber at 25°C and 75% relative humidity (RH). The seeds sample were classified into germinated and dead seeds by naked eyes each day according to whether sprout came out or not. Then, the germinated seeds were counted every day for up to 7 days. The average of three replicates is considered.

2.5.9.3 Colour test

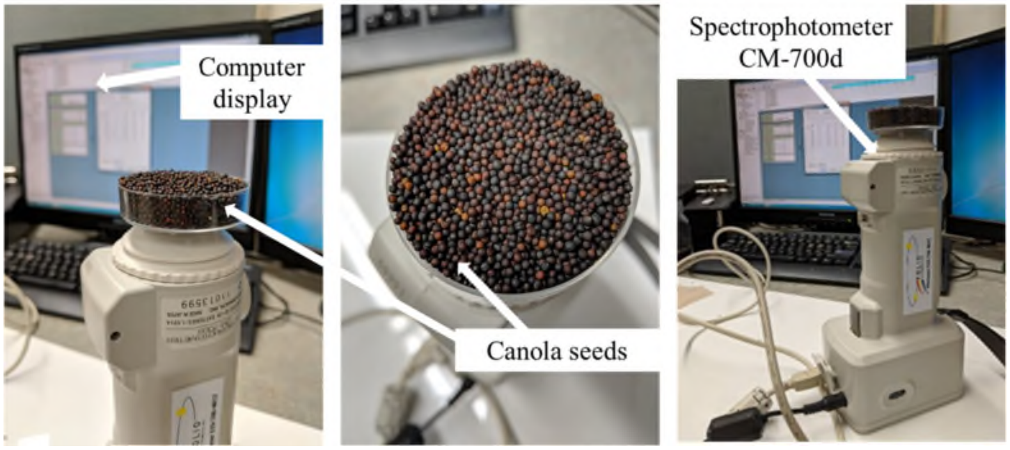


Figure 2.7: Spectrophotometer CM-700d (Folio Instruments Inc., Konica Minolta, Inc. Japan).

Spectrophotometer CM-700d, as shown in Figure 2.7 (Folio Instruments Inc., Konica Minolta, Inc. Japan) was used to measure the surface colour of the canola seeds by pouring the seeds on a petri dish and then placed on the stage of the spectrophotometer. Spectrophotometer CM-700d is recommended by Folio Instruments Inc. to be operated at temperature and humidity range of 5°C to 40°C and RH of 80% or less (at 35°C) with no condensation, and the measurement time was approximately 1 s. The CIELAB (CIE L*a*b*) colour space was used to record the colour of canola seeds. CIELAB expresses colour as a combination of three values, where, L* represents the lightness from black (0) to white (100), a* represents the space between green (-) to red (+), and b* represents the space between blue (-) to yellow (+).

2.5.9.4 Oil quality analysis

We allowed the RF treated samples to cool down to room temperature (22°C) sealed in Ziploc® bags and stored in cold storage at 4°C. We extracted the canola the oil extraction using Komet Oil Press CA59G, as shown in Figure 2.8 and filtered through a Whatman # 1 filter paper. We used the filtrated oil to evaluate the oxidative stability, the peroxide value (PV) and the p-Anisidine value (AV) following the American Oil Chemists' Society (AOCS) Official Methods Cd 8-53 and Cd 18-90 (AOCS, 1993) respectively. Then we calculated the overall oxidative stability as the total oxidation (TOTOX) value;

$$\text{TOTOX value} = 2PV+AV \quad (2.4)$$

Low TOTOX values indicate a better quality of the oil.

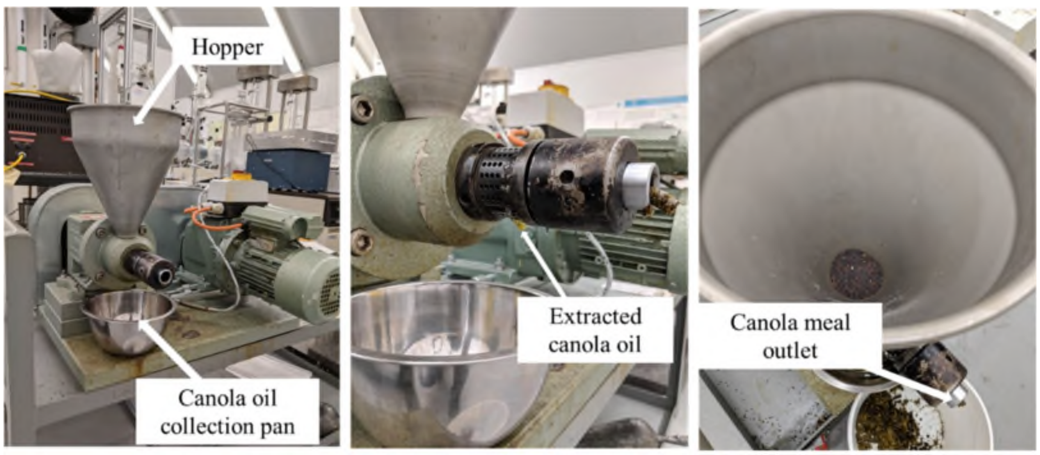


Figure 2.8: Oil extraction using Komet Oil Press CA59G.

2.5.10 Data analysis

We triplicated all the experiments and processed and analyzed data using SPSS. We have used Tukey HSD test to determine the statistical differences of the temperatures, power level, and seed quality analysis. Means of the triplicates for each treatment combination were compared for significance at 5% probability level using Tukey HSD test.

2.6 Results and discussions

2.6.1 Hottest and coldest spot in the bulk canola

Bags containing 9% MC (w.b.) canola seeds were heated from an initial temperature of 24°C to the final temperature of 75°C. The canola seeds were at room temperature (22℃) but for the temperature history presentation, the initial temperature was reported from 24℃ to maintain a consistent start temperature, as the room temperature was slightly variable. Temperatures histories were recorded at 21 different locations for 9% MC (w.b.) using a 50-ohm RF heating system at 3 kW, 5 kW, and 7 kW. There was non-uniformity in the heating rates at all the locations. Table 2.1 shows the temperature histories and the heating rates for 9% MC (w.b.) canola seeds at 21 different locations during 3 kW, 5 kW, and 7 kW RF heating along with the temperature histories. Location 1 heated significantly (Table 2.1) faster than other Locations at all the power levels reaching 75℃ from 24℃ in 530 s, 300 s, and 200 s at 3 kW, 5 kW, and 7 kW respectively. Thus, generating faster heating rates (3 kW-1 0.095°C/s, 5 kW-0.170°C/s, and 7 kW-0.254°C/s) in all the conditions. Also, the heating rate at Location 1 increased significantly (Table 2.1) as the RF power levels increased which agrees the statement that the electric field intensity (E) is directly proportional to the heating rate, so, the higher the power dissipation on the material, the higher the increase in temperature (Shrestha et al., 2013b; Shrestha and Baik, 2013). Location 1 was found to the hottest spot and the temperature was much higher than the adjacent positions (Location 10, Location 4, and Location 13) in the same zone. However, reliable speculation on the phenomenon could not be established relying only on literature. Detailed computer simulations are required to understand the physics behind the heating pattern in the 50-ohm RF heating system.

Table 2.1. Temperature histories and heating rates for 9% moisture content (wet basis) canola seeds at 21 different locations in during 3 kW (n = 21), 5 kW (n = 21), and 7 kW (n = 21) radio frequency heating.

Locations	**Temperature (°C)**			**Heating rate (ΔT/Δt) (°C/s)**		
	3 kW	5 kW	7 kW	3 kW	5 kW	7 kW
1	$_{m}$74.8±0.3^{a}	$_{q}$75.0±0.2^{a}	$_{h}$74.8±1.2^{a}	$_{l}$0.095±0.000^{a}	$_{q}$0.170±0.000^{b}	$_{g}$0.254±0.006^{c}
2	$_{l}$56.4±0.5^{a}	$_{p}$71.8±0.2^{b}	$_{g}$57.2±1.7^{a}	$_{k}$0.061±0.000^{a}	$_{p}$0.159±0.000^{b}	$_{f}$0.166±0.008^{b}

3	${}_{kl}56.0\pm0.2^{a}$	${}_{o}59.7\pm0.3^{b}$	${}_{ef}46.3\pm0.2^{b}$	${}_{jk}0.060\pm0.000^{a}$	${}_{o}0.119\pm0.001^{b}$	${}_{de}0.111\pm0.025^{b}$
4	${}_{j}50.9\pm0.2^{c}$	${}_{m}46.1\pm0.2^{b}$	${}_{cde}43.0\pm0.4^{a}$	${}_{i}0.050\pm0.000^{a}$	${}_{m}0.073\pm0.000^{b}$	${}_{cd}0.095\pm0.002^{c}$
5	${}_{k}55.0\pm0.2^{c}$	${}_{m}46.5\pm0.4^{b}$	${}_{bcde}42.1\pm1.38^{a}$	${}_{j}0.058\pm0.000^{a}$	${}_{m}0.075\pm0.001^{b}$	${}_{bcd}0.090\pm0.006^{c}$
6	${}_{hi}45.7\pm0.3^{b}$	${}_{ghi}41.7\pm0.3^{ab}$	${}_{abc}38.03\pm3.6^{a}$	${}_{h}0.041\pm0.000^{a}$	${}_{ghi}0.059\pm0.001^{a}$	${}_{abc}0.070\pm0.018^{b}$
7	${}_{h}45.8\pm0.2^{c}$	${}_{jk}42.8\pm0.2^{b}$	${}_{a}36.3\pm1.0^{a}$	${}_{h}0.041\pm0.000^{a}$	${}_{jk}0.062\pm0.000^{b}$	${}_{a}0.061\pm0.005^{b}$
8	${}_{fg}41.9\pm0.2^{c}$	${}_{gh}41.3\pm0.2^{b}$	${}_{abcd}39.0\pm0.05^{a}$	${}_{f}0.033\pm0.000^{a}$	${}_{gh}0.057\pm0.000^{b}$	${}_{abc}0.075\pm0.000^{c}$
9	${}_{bc}38.8\pm0.3^{a}$	${}_{d}38.0\pm0.2^{a}$	${}_{a}35.9\pm2.7^{a}$	${}_{bcd}0.028\pm0.000^{a}$	${}_{d}0.046\pm0.000^{ab}$	${}_{a}0.059\pm0.013^{b}$
10	${}_{hi}44.6\pm0.3^{a}$	${}_{k}43.6\pm0.4^{a}$	${}_{ef}47.6\pm1.9^{b}$	${}_{h}0.039\pm0.000^{a}$	${}_{k}0.065\pm0.001^{b}$	${}_{de}0.118\pm0.009^{c}$
11	${}_{fg}41.8\pm0.2^{a}$	${}_{ij}42.5\pm0.3^{a}$	${}_{cde}42.7\pm0.4^{a}$	${}_{fg}0.033\pm0.000^{a}$	${}_{ijk}0.062\pm0.001^{b}$	${}_{cd}0.093\pm0.002^{c}$
12	${}_{g}42.5\pm0.4^{a}$	${}_{ef}49.9\pm0.2^{a}$	${}_{abcd}40.0\pm2.6^{a}$	${}_{g}0.035\pm0.000^{a}$	${}_{ef}0.053\pm0.000^{b}$	${}_{abc}0.080\pm0.011^{c}$
13	${}_{j}50.9\pm0.2^{b}$	${}_{n}48.2\pm0.4^{a}$	${}_{f}50.9\pm0.5^{b}$	${}_{i}0.050\pm0.000^{a}$	${}_{n}0.080\pm0.001^{b}$	${}_{e}0.134\pm0.002^{c}$
14	${}_{fg}41.8\pm0.2^{a}$	${}_{hij}42.0\pm0.2^{a}$	${}_{abcd}40.3\pm1.3^{a}$	${}_{fg}0.033\pm0.000^{a}$	${}_{hij}0.060\pm0.000^{b}$	${}_{abc}0.081\pm0.006^{c}$
15	${}_{hi}45.7\pm0.3^{c}$	${}_{fg}40.9\pm0.2^{b}$	${}_{ab}36.7\pm0.9^{a}$	${}_{h}0.041\pm0.000^{a}$	${}_{fg}0.056\pm0.000^{b}$	${}_{ab}0.063\pm0.004^{c}$
16	${}_{a}37.8\pm0.3^{c}$	${}_{a}33.9\pm0.2^{a}$	${}_{a}36.2\pm0.7^{b}$	${}_{ab}0.026\pm0.000^{a}$	${}_{a}0.029\pm0.000^{a}$	${}_{a}0.061\pm0.003^{b}$
17	${}_{bc}38.5\pm0.4^{a}$	${}_{e}39.6\pm0.4^{a}$	${}_{acb}38.2\pm1.4^{a}$	${}_{bcd}0.027\pm0.000^{a}$	${}_{e}0.052\pm0.001^{b}$	${}_{abc}0.071\pm0.007^{c}$
18	${}_{ef}40.8\pm0.3^{b}$	${}_{c}36.5\pm0.4^{a}$	${}_{a}35.6\pm0.5^{a}$	${}_{ef}0.030\pm0.000^{a}$	${}_{c}0.041\pm0.001^{b}$	${}_{a}0.058\pm0.002^{c}$
19	${}_{a}37\pm0.5^{b}$	${}_{b}34.9\pm0.2^{a}$	${}_{ab}36.9\pm0.3^{b}$	${}_{a}0.024\pm0.001^{a}$	${}_{b}0.036\pm0.000^{b}$	${}_{ab}0.064\pm0.001^{c}$
20	${}_{cd}39.4\pm0.5^{a}$	${}_{de}38.9\pm0.2^{a}$	${}_{abcd}39.7\pm0.0^{a}$	${}_{cde}0.029\pm0.000^{a}$	${}_{de}0.049\pm0.000^{b}$	${}_{abc}0.078\pm0.000^{c}$
21	${}_{de}40.3\pm0.5^{a}$	${}_{d}38.5\pm0.4^{a}$	${}_{a}34.8\pm0.9^{a}$	${}_{de}0.030\pm0.001^{a}$	${}_{d}0.048\pm0.001^{b}$	${}_{a}0.054\pm0.004^{b}$
Average temperature	${}_{i}46.0\pm0.6^{c}$	${}_{l}44.8\pm0.2^{b}$	${}_{de}44.5\pm0.3^{a}$	${}_{h}0.041\pm0.000^{a}$	${}_{l}0.069\pm0.000^{b}$	${}_{cd}0.092\pm0.001^{c}$

Note: Each mean represents the average of three replicates and represented as mean ± σ. Mean in column with different subcripted alphabets are under Temperature column and Heating rate colums are significantly ($p < 0.05$) different. Mean in rows with different supercripted alphabets are under Temperature column are significantly ($p < 0.05$) different. Mean in rows with different supercripted alphabets are under Heating rate column are significantly ($p < 0.05$) different. Significance test: Tukey HSD test.

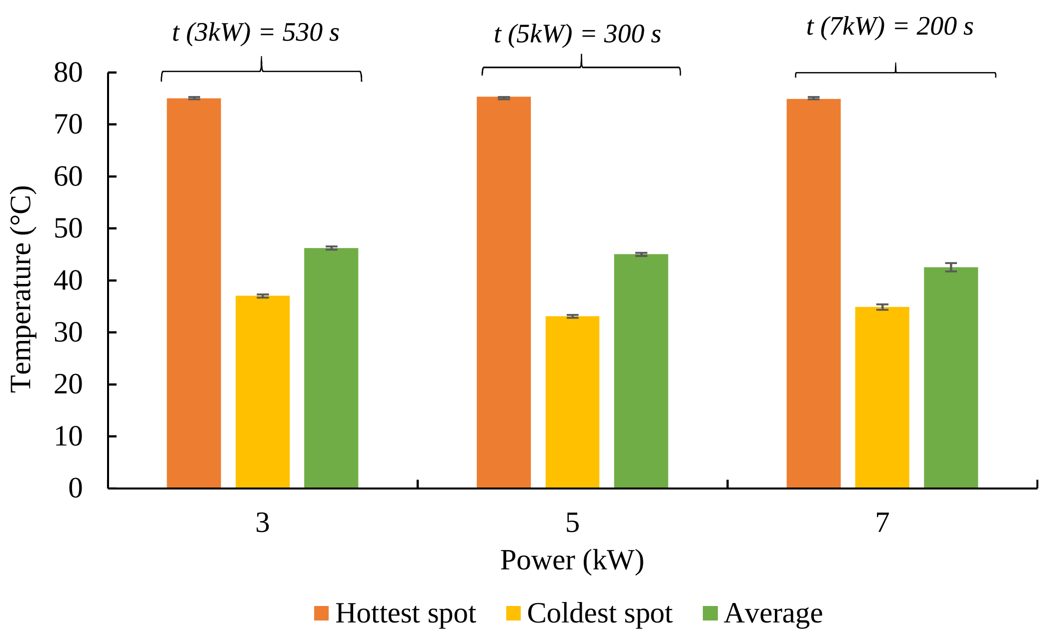


Figure 2.9: Final temperature at hottest spots, coldest spots and average final temperature of the bulk canola after RF heating time of 530 s, 300 s, and 200 s for 3 kW (n = 21), 5 kW (n = 21), and 7 kW (n = 21), respectively.

Location 1 was consistently the hottest spot in all the conditions, which was in the front zone of the electrode just adjacent (8 cm) to the hot electrode. The lowest heating rates were found in Location 19 (0.0245°C/s, the upper left corner in the front zone of the applicator), Location 16 (0.0303°C/s, the upper right corner in the front zone of the applicator), and Location 21 (0.0543°C/s, the upper left corner in the back zone of the applicator) for 3 kW, 5 kW and 7 kW RF heating, respectively. Figure 2.9 shows the difference in final temperature at the hottest spot

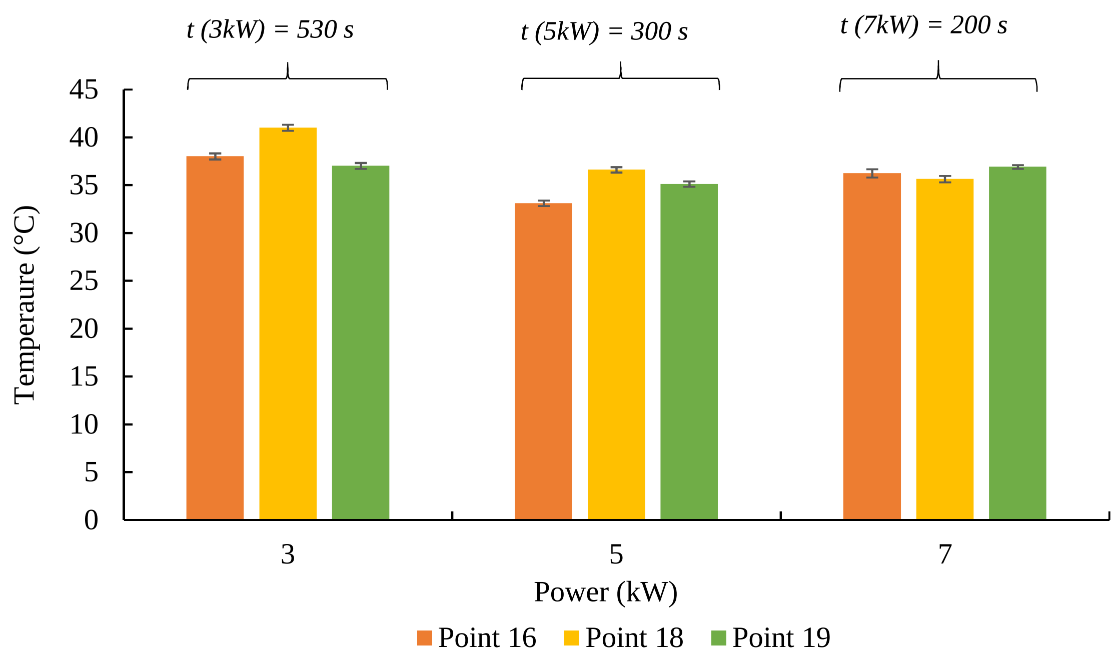


Figure 2.10: Final temperature at cold spots (Location 16, Location 19 and Location 21) of the bulk canola after RF heating time of 530 s, 300 s and 200 s for 3 kW (n = 21), 5 kW (n = 21), and 7 kW (n = 21) respectively.

and coldest spots after RF heating time of 530 s, 300 s and 200 s for 3 kW, 5 kW, and 7 kW respectively. Interestingly, although the hottest spot is observed consistently at Location 1 in all the conditions, the cold spots are scattered to Location 19, Location 16 and Location 21 for 3 kW, 5 kW and 7 kW respectively. So, looking into these locations in 3 kW, 5 kW, and 7 kW RF heating, the temperatures at these locations are relatively like one another. Figure 2.10 shows the final temperatures of bulk canola at Location 16, Location 19 and Location 21.

These observations imply that the location of the hottest spot and coldest spots are on the edges. In general, the final temperatures of bulk canola samples adjacent to the cold electrode were lower than that of bulk samples adjacent to the hot electrode. Several interacting factors influence temperature distribution in RF heating, distribution of the electromagnetic field during RF heating of the samples is however considered to be a major factor (Huang et al. 2016a, 2016b; Wang et al. 2007). Temperature distribution in RF heating is also affected but also by the size, shape, and position of the sample in the RF applicator along with the thermal, physical, and electrical properties of the sample (Yu et al. 2016a).

According to Huang et al. (2018), the electric field strength is uniform in parallel plate electrodes, when there is no sample present. However, introducing samples at the bottom electrode with an air gap at the top electrode, the electric field strength was not uniform. They explained this phenomenon as charged particles from the top electrode (hot electrode) attracted the opposite charges from the bottom electrode, causing the electric field. Since the sample was not present, the electric field was free to go to the less resistance region (conductor). The presence of two different components present in between the electrodes, one being the sample and the other being air could be the cause of non-uniformity in the electric field when the samples were present at the bottom electrode with an air gap. As air serves as an insulator and it has more resistance and fewer charges present. The electric field avoids the air and prefers to travel through the dielectric materials or to a conductor electrode. The electric field coming from the corners and edges of the electrodes moves to the closer materials with more charges (dielectric or conductive materials). Huang et al. (2018) also observed that when the electrode size and sample size were similar heating was uniform, comparing to the ones where the sample size is smaller than that of electrodes. Also, when the electrode was larger than the sample, Llave et al. (2015) reported that the electric field intensity was higher in the corner of the sample closest to the electrodes. Also, they observed the irregular distribution of temperature when electrodes were smaller than the sample. However, when the electrodes were of the same size as the sample material, there was an edge effect, resulting in an intensification of the electric field there and non-uniform heating occurred.

Similarly, other research has also suggested that temperature variation occurs during RF heating, and non-uniform heating rate distribution occurs irrespective of the MCs and sample volumes (Yu et al. 2016a, Jiao et al. 2015, Alfaifi et al. 2014, Gao et al., 2010). The applicator had a polypropylene composite component, which was hollow (cylindrical) at the center to hold the samples, at higher frequency (> 3 kHz) polymer composites (Polyethylene/polypropylene) tends to exhibit ionic polarization (Dabbak et al. 2018), this property of the materials also might have interfered with the electric field causing disturbance in the heating mechanism. Figure 11 shows the concentration of the electric field at the edges along with the deflection of the electric field through the outer and inner conductors in a typical 50-ohm RF heating system with parallel plate electrodes. Llave et al. (2015) observed the importance of electrode size and sample size, they found that the electric field intensity to be higher in the corner of the sample closest to the electrodes. When electrodes smaller than the sample were considered, irregular temperature distribution was observed. However, when the electrodes were of the same size as the sample material, there was edge effect, which is faster heating rates at the corners of the sample, resulting in an intensification of the electric field there causing non-uniform heating rate distribution (Llave et al. 2015). Similar observations were recorded, as in this study the length of the electrode was identical to the length of the canola bags and the hottest spot was recorded on the tubular wall of the applicator (Location 1). Also, the air present in between the particles of the bulk canola must have influenced the heating pattern, since, the air has different dielectric properties to the canola grains causing uneven distribution in the heating rates throughout the sample load. However, since

RF field distribution relies on several parameters, computer simulations are necessary to obtain the exact RF field distribution in a 50-ohm RF heating system.

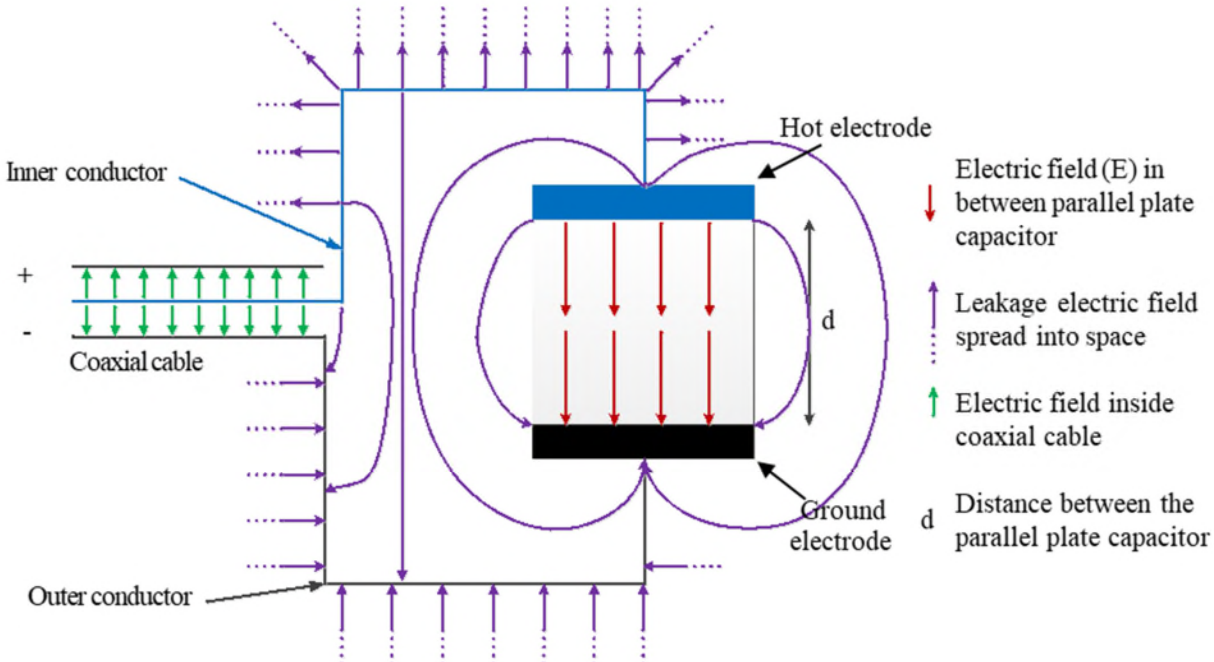


Figure 2.11: Schematic of edge heating within two parallel electrodes under the radio frequency electric field (E). Adapted from Ferdous (2015).

2.6.2 Temperature distribution of the canola seeds

2.6.2.1 Temperature distribution in each of the polypropylene bags containing bulk canola samples

Apart from dielectric heating, heat transfer also occurs by conduction, transferring heat from the hotter canola seeds to the colder canola seeds due to the difference in temperature between them. Also, during heating of the canola seeds vapor is released from the hottest spot at higher temperature which encourages the convection heat transfer. Due to the presence of polypropylene layers (bags) the movement of vapor could have been restricted, thus, it was important to understand the role of vapor generation and its influence in temperature distribution in each bag which was given by the θ of each bag. Also, each canola bag weas located at different heights from the hot electrode, so, the comparison of the average temperature (T_{avg}) of each canola bag was essential to understand the temperature distribution in the bulk canola for the distance from the hot electrode. The temperature histories of each bag at three different locations were considered. Table 1.2 shows the θ and average temperature (T_{avg}) of bulk canola in different polypropylene bags and placed throughout the applicator. B1 which is located closest to the hot electrode shows the highest T_{avg} of 62.6°C, 69.06°C, and 59.4°C at 3 kW, 5 kW, and 7 kW. The T_{avg} at 7 kW was significantly lower than that of 3 kW and 5 kW, as at 7 kW the heating time was much lesser in relation to 3 kW and 5 kW, the time for conductive heat loss from hotter canola seeds to colder ones are shorter, which increased the efficiency of selective heating at higher RF power. There were larger differences in the change of temperature in the hottest spot and colder ones in B1 at 7 kW compared to 3 kW and 5 kW, thus, the T_{avg} of B1 is the lowest in 7 kW. Regarding the θ of B1 5 kW showed the least value of 0.17 and the highest value of 0.40 at 7 kW. The central axis of the B4 cylindrical canola bag is located at a height of 10 cm from the hot (bottom) electrode showed the least θ value of 0.07 with T_{avg} of 43.16℃ when subjected to 3 kW RF heating; similarly, B4 showed the least θ value of 0.10 with T_{avg} of 42.16℃ when subjected to 5 kW RF heating. At 7 kW the location changes to cylindrical bag B6, where the central axis of the cylinder is located 20 cm from the hot (bottom) electrode, with θ value of 0.10 and T_{avg} of 36.71℃. However, the θ values of the canola bags were not significantly different from one another, nor the increase in RF power level changed the θ value significantly (Table 2.2). Thus, the T_{avg} decreases with the increase of height, the bags near the hot (bottom) electrode heated relatively faster than those near the cold (upper) electrode. Each canola cylindrical bag had θ values less than 0.3 in all the bags in 5 kW, in 3 kW and the 5 kW accept at B1 θ values of all the other bags were less than 0.3. Although the θ value at B1 in 3 kW and 7 kW were not significantly different from the other canola bags, thus, suggesting each bag had uniform temperature distribution. By subdividing the bulk canola samples into seven different polypropylene bags; the migration of vapor from the hotter region near the hot electrode to the inner colder region of the sample did not happen. Thus, causing the non-uniform distribution of temperature throughout the heating chamber. T_{avg} and θ with respect to the height from the hot (bottom) electrode do not explain the complete picture, so it is necessary to study the characteristics of T_{avg} and θ with respect to the distance from the front zone of the applicator.

Table 2.2: Uniformity index and average temperature of bulk canola in different polypropylene bags and different zones placed throughout the applicator.

Bag number or zone	**Length or height (cm)**	**Average temperature**			**Uniformity index**		
		3 kW (time = 530 s)	5 kW (time = 300 s)	7 kW (time = 200 s)	3 kW	5 kW	7 kW
Bag = 1	h=8	$_{b}62.6\pm10.7^{a}$	$_{b}69.06\pm8.0^{a}$	$_{b}59.4\pm14.3^{a}$	$_{a}0.312\pm0.151^{a}$	$_{a}0.195\pm0.063^{a}$	$_{a}0.307\pm0.140^{a}$
Bag = 4	h=13	$_{a}43.16\pm1.4^{a}$	$_{a}42.16\pm1.9^{a}$	$_{ab}43.46\pm3.8^{a}$	$_{a}0.086\pm0.015^{a}$	$_{a}0.186\pm0.094^{a}$	$_{a}0.148\pm0.099^{a}$
Bag = 5	h=13	$_{a}46.4\pm4.6^{a}$	$_{a}43.89\pm3.9^{a}$	$_{ab}42.66\pm7.3^{a}$	$_{a}0.253\pm0.095^{a}$	$_{a}0.198\pm0.127^{a}$	$_{a}0.268\pm0.112^{a}$
Bag = 2	h=18	$_{ab}50.83\pm4.6^{b}$	$_{a}44.93\pm2.6^{ab}$	$_{a}41.05\pm2.6^{a}$	$_{a}0.112\pm0.074^{a}$	$_{a}0.186\pm0.048^{a}$	$_{a}0.185\pm0.055^{a}$
Bag = 6	h=23	$_{a}39.2\pm1.5^{a}$	$_{a}36.46\pm3.5^{a}$	$_{a}36.71\pm1.4^{a}$	$_{a}0.158\pm0.091^{a}$	$_{a}0.158\pm0.117^{a}$	$_{a}0.182\pm0.085^{a}$
Bag = 7	h=23	$_{a}38.9\pm1.7^{a}$	$_{a}37.59\pm2.2^{a}$	$_{a}37.16\pm2.4^{a}$	$_{a}0.146\pm0.027^{a}$	$_{a}0.172\pm0.059^{a}$	$_{a}0.149\pm0.025^{a}$
Bag = 3	h=28	$_{a}42.43\pm3.1^{a}$	$_{a}40.93\pm2.4^{a}$	$_{a}37.11\pm1.6^{a}$	$_{a}0.152\pm0.036^{a}$	$_{a}0.189\pm0.056^{a}$	$_{a}0.157\pm0.037^{a}$
Zone = outer	l=5	$_{a}49.04\pm0.30^{a}$	$_{a}46.42\pm0.20^{a}$	$_{a}46.55\pm0.10^{a}$	$_{a}0.511\pm0.008^{a}$	$_{c}0.624\pm0.009^{a}$	$_{b}0.611\pm0.019^{a}$
Zone = middle	l=35	$_{a}45.0\pm0.30^{a}$	$_{a}46.12\pm0.25^{a}$	$_{a}42.7\pm0.31^{a}$	$_{b}0.354\pm0.006^{a}$	$_{b}0.524\pm0.004^{a}$	$_{a}0.352\pm0.048^{a}$
Zone = back	l=65	$_{a}44.42\pm0.30^{a}$	$_{a}42.33\pm0.31^{a}$	$_{a}38.22\pm0.92^{a}$	$_{b}0.288\pm0.009^{a}$	$_{a}0.436\pm0.007^{a}$	$_{a}0.303\pm0.151^{a}$

Note: Each mean represents the average of three replicates and represented as mean ± σ. Mean of each Bag in the same row with different supercripted alphabets under T_{avg} are significantly ($p < 0.05$) different according to Tukey HSD analysis. Mean of each Bag in the same row with different supercripted alphabets under θ are significantly ($p < 0.05$) different according to Tukey HSD analysis. Mean of each Zone in the same row with different supercripted alphabets under T_{avg} are significantly ($p < 0.05$) different according to Tukey HSD analysis. Mean of each Zone in the same row with different supercripted alphabets under θ are significantly ($p < 0.05$) different according to Tukey HSD analysis.

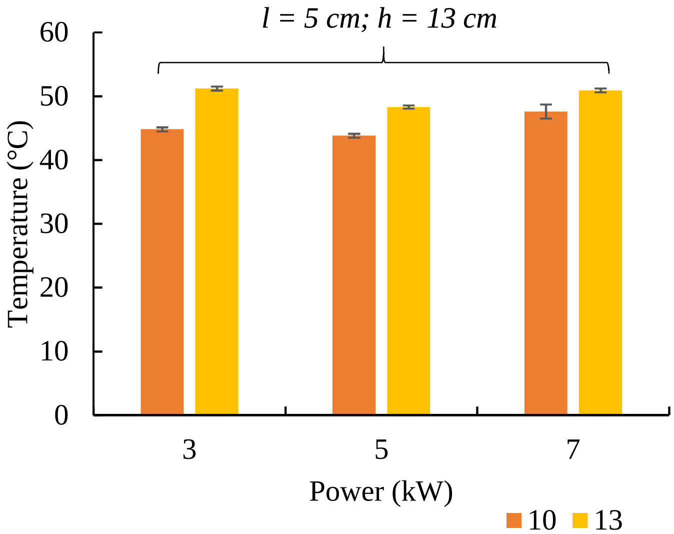
2.6.2.2 Temperature distribution of bulk canola samples in different zones

The bulk canola in the applicator was divided into three zones; front zone, middle zone, and back zone. The front zone was located 5 cm from the mouth of the applicator, the middle zone was located 35 cm from the mouth of the applicator and the back zone was located 65 cm from the mouth of the applicator (Figure 2.6). Table 2.2 shows the θ and T_{avg} of bulk canola at different locations situated in different zones throughout the applicator. θ of bulk canola at the front zone were 0.509, 0.62, and 0.61 for 3 kW, 5 kW, and 7 kW respectively suggesting temperature distribution to be more uniform at 3 kW comparing to 5 kW, and 7 kW. Whereas T_{avg} of bulk canola of the front zone at 3 kW was higher than that of 5 kW, and 7 kW. Unlike the front zone, θ of bulk canola at the middle zone were 0.415, 0.521, and 0.35 for 3 kW, 5 kW, and 7 kW respectively suggesting the temperature distribution to be more uniform at 7 kW compared to 3 kW, and 5 kW. Whereas, T_{avg} of bulk canola in the middle zone was higher at 5 kW comparing to 3 kW and 7 kW. Also, the θ of bulk canola at back zone were 0.287, 0.433, and 0.278 for 3 kW, 5 kW, and 7 kW respectively suggesting the temperature distribution to be more uniform at 7 kW comparing to 3 kW and 5 kW, and the T_{avg} of bulk canola at inner zone was higher at 3 kW comparing to 5 kW and 7 kW. Generally, T_{avg} decreases with an increase in distance from the mouth of the applicator and the difference in T_{avg} between the hottest zone (front) and coldest zone (back) was the highest at 7 kW (Table 2.2).

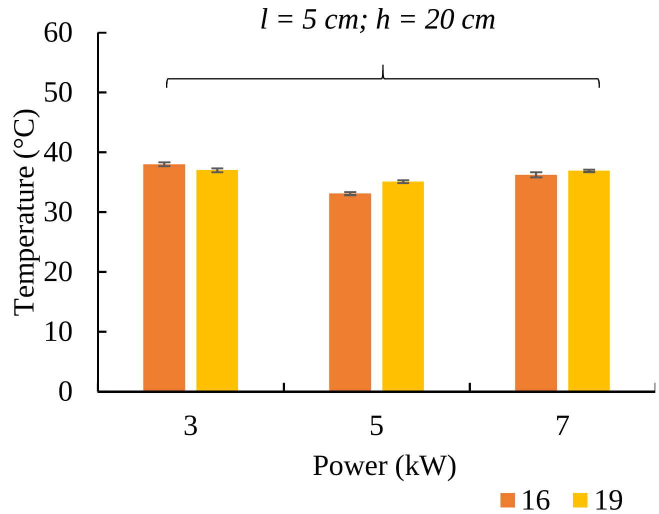
2.6.2.3 Temperature distribution on the left and right sides of bulk canola in the applicator

Canola bags B4, B5, B6, and B7 were considered to study the symmetrical behavior of θ and T_{avg} of the bags and different zones. The location B4 and B6 were on the left side of the applicator; likewise, B5 and B7 on the right side in the applicator. The height of the central axis of cylinders of B4 and B5 were identical, 13 cm from the hot (bottom) electrode. Likewise, the central axis of cylinders of B6 and B7 were located identical heights, 23 cm from the hot (bottom) electrode. Regarding the zones, the front zone was located 5 cm from the mouth of the applicator and consisted the following Locations: 1, 4, 7, 10, 13, 16, and 19; middle zone was located 35 cm from the mouth of the applicator and consisted the following Locations: 2, 5, 8, 11, 14, 17, and 20; and back zone was located 65 cm from the mouth of the applicator consisted the following Locations: 3, 6, 9, 12, 15, 18, and 21. Since bags B4 and B6 were symmetrically aligned to bags B5and B7 on left and right side of the central axis of the tubular applicator respectively, it was critical to study the symmetrical heating rate characteristics at these points. Figure 2.12 shows the difference of average ΔT of the identical locations situated at the left and right sides of bulk canola in the applicator. At the height of 13 cm from the hot (bottom) electrode, the left side (B4) heated significantly faster than that of the right side (B5), at 3 kW ($p = 0.008$) and 5 kW ($p = 0.044$), but the difference in heating rates of B5 and B4 were not significant at 7 kW ($p = 0.516$). At the height of 23 cm from the hot (bottom) electrode, the right side (B7) heated significantly faster the left side (B6), at 5 kW ($p = 0.030$), however, no significant difference in the heating rates of B6 and B7 were observed at 3 kW ($p = 0.392$) and 7 kW ($p = 0.329$).

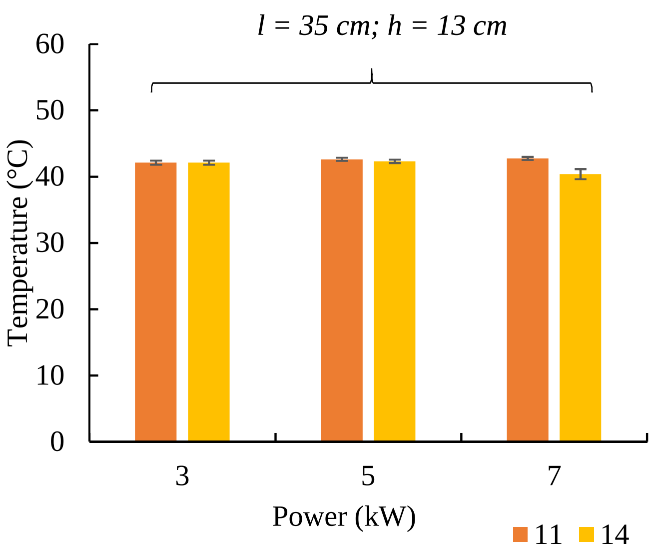
Considering the different zones, the front zone was located at 5 cm from the mouth of the tubular applicator (Figure 2.6), the locations considered were 10 and 19 on the left side of the central axis of the applicator and locations 13 and 16 on the right. The middle zone was located at 35 cm from the mouth of the tubular applicator (Figure 2.6), the locations considered were 11 and 20 on the left side of the central axis of the applicator and locations 14 and 17 on the right. Back zone was located at 65 cm from the mouth of the tubular applicator (Figure 2.6), the locations considered were 12 and 21 on the left side of the central axis of the applicator and locations 15 and 18 on the right. In the front zone the right side heated up at significantly faster rate than the left side at 3 kW ($p = 0.027$) but the heating rates were not significantly different at 5 kW ($p = 0.425$) and 7 kW ($p = 0.272$). In the middle zone the left side heated up at significantly faster rate than the right side at 7 kW ($p = 0.021$), but the heating rates at 3 kW ($p = 0.075$) and 5 kW ($p = 0.577$) were not significantly different from the left to the right side. In the back zone the left side heated up at significantly faster rate than the right side at 7 kW ($p = 0.028$), but at 3 kW ($p = 0.018$) the right side heated at a significantly faster rate than the left side. However, at 5 kW ($p = 0.490$) the heating rates were not significantly different from the left to the right side. So, the heating pattern is not symmetric as there are differences in final temperatures on the left and right sides of bulk canola in the applicator.


l = 5 cm; h = 13 cm
Temperature (°C)
0
10
20
30
40
50
60
3
5
7
Power (kW)
10
13

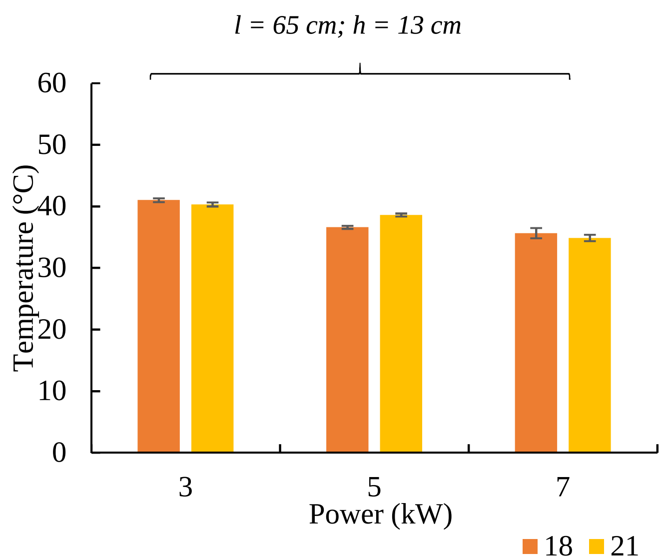
(a)


l = 5 cm; h = 20 cm
Temperature (°C)
0
10
20
30
40
50
60
3
5
7
Power (kW)
16
19

(b)


l = 35 cm; h = 13 cm
Temperature (°C)
0
10
20
30
40
50
60
3
5
7
Power (kW)
11
14

(c)


l = 65 cm; h = 13 cm
Temperature (°C)
0
10
20
30
40
50
60
3
5
7
Power (kW)
18
21

(d)

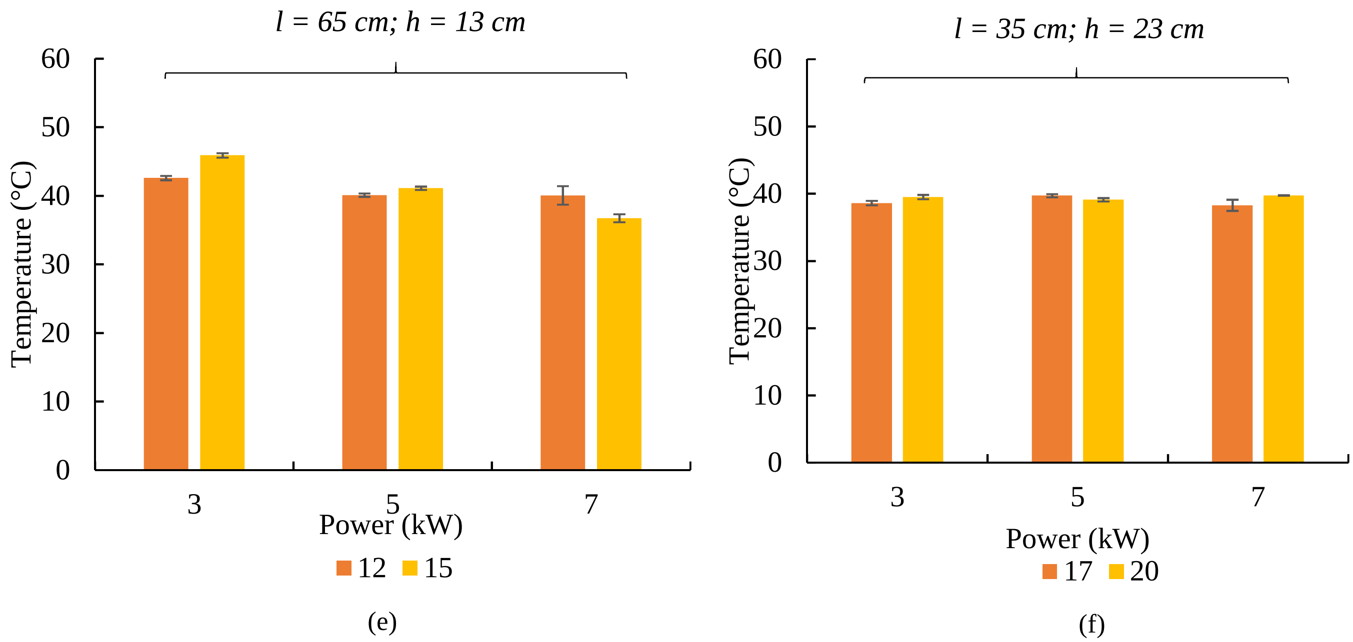


Figure 2.12: Comparison of final temperature of different locations located in left and right side of bulk canola in the applicator at 3 kW, 5 kW, and 7 kW 50 ohm RF heating (a) Location 10 and Location 13 (b) Location 16 and Location 19 (c) Location 11 and Location 14 (d) Location 17 and Location 20 (e) Location 12 and Location 15 (f) Location 18 and Location 21. Note: Error bars represent the standard mean errors.

2.6.3 Seed quality

Different parameters that defined the quality of canola seeds including the comparison of MC, germination rate, colour and oil quality of canola seeds before and after RF heating at various end temperatures and various power levels were considered. The seed quality analysis was carried only to the grains heated to 50°C, 55°C, 60°C, and 65°C from the hottest spot (Location 1). The quality changes are subjected to reaction kinetics and the important parameters are time and temperature. Thus, Location 1 was chosen in all the RF power levels, which consistently produced the fastest heating rates.

2.6.3.1 Moisture content

Table 2.3 shows the change of moisture MC from 9% MC (w.b) to the final MC at various final temperatures. The change is the highest at 65°C which are 2.70, 2.63, and 2.65% at 3 kW, 5 kW, and 7 kW respectively and lowest at 50°C which are 2.28, 2.27, and 2.34% at 3 kW, 5 kW, and 7 kW. The change in MC from initial MC to final MC gradually increases with the increase of temperature; however, with the increase in power, the difference in MC remains relatively similar.

Table 2.3. Change in moisture content of canola seeds at various final temperatures at various power levels using 50-ohm radio frequency heating.

Power (kW)	Temperature (°C)	Initial moisture content (% wet basis)	Final moisture content (% wet basis)	Initial moisture content - Final moisture content (% wet basis)
No treatment	4	${}_{a}9.00\pm0.00^{b}$	${}_{d}9.00\pm0.00^{b}$	${}_{a}0.00\pm0.00^{a}$
3	50	${}_{a}9.04\pm0.01^{c}$	${}_{c}6.76\pm0.01^{b}$	${}_{b}2.28\pm0.03^{a}$
3	55	${}_{a}9.02\pm0.02^{c}$	${}_{c}6.79\pm0.05b^{b}$	${}_{b}2.25\pm0.06^{a}$
3	60	${}_{a}9.05\pm0.03^{c}$	${}_{cb}6.74\pm0.08^{b}$	${}_{b}2.30\pm0.05^{a}$
3	65	${}_{a}9.04\pm0.03^{c}$	${}_{a}6.34\pm0.29^{b}$	${}_{d}2.70\pm0.28^{a}$
5	50	${}_{a}9.04\pm0.01^{c}$	${}_{c}6.77\pm0.11^{b}$	${}_{b}2.27\pm0.02^{a}$
5	55	${}_{a}9.03\pm0.02^{c}$	${}_{c}6.77\pm0.01^{b}$	${}_{b}2.26\pm0.04^{a}$
5	60	${}_{a}9.06\pm0.03^{c}$	${}_{c}6.77\pm0.07^{b}$	${}_{b}2.28\pm0.07^{a}$
5	65	${}_{a}9.01\pm0.01^{c}$	${}_{a}6.38\pm0.07^{b}$	${}_{c}2.63\pm0.08^{a}$
7	50	${}_{a}9.00\pm0.00^{c}$	${}_{b}6.66\pm0.06^{b}$	${}_{b}2.34\pm0.06^{a}$
7	55	${}_{a}9.00\pm0.00^{c}$	${}_{c}6.77\pm0.12^{b}$	${}_{b}2.23\pm0.12^{a}$
7	60	${}_{a}9.00\pm0.00^{c}$	${}_{cb}6.73\pm0.30^{b}$	${}_{b}2.27\pm0.30^{a}$
7	65	${}_{a}9.00\pm0.00^{c}$	${}_{a}6.35\pm0.25^{b}$	${}_{cd}2.65\pm0.25^{a}$

Note: Each mean represents the average of three replicates and represented as mean ± σ. Different subscripted alphabets in the same column indicate statistically significant ($p < 0.05$) according to Tukey HSD test. Different superscripted alphabets in the same rows indicate statistically significant ($p < 0.05$) according to Tukey HSD test.

2.6.3.2 Germination rate

Table 2.4 shows the germination rate of the non-treated and RF heated canola seeds at various final temperatures. There was a significant increment in germination rate at 60°C in all the power levels with average values of 10, 9.6, and 10.0 at 3 kW, 5 kW, and 7 kW, respectively (Table 2.4). Similarly, Yu et al. (2016) stated, no substantial loss of germination of canola seeds at different MC, occurred at temperature up to 60°C using RF heating. However, the lowest average numbers of germinated seeds were 9.0, 8.6, and 8.6 at 3 kW, 5 kW, and 7 kW, respectively at 65°C, which were significantly different from non-RF treated canola seeds (Table 2.4). Also, the increment of power level significantly reduced the germination rates as the lowest average number of germinated seeds at 65°C. The RF heating might have changed the physiochemical quality of canola seeds affecting germination once the temperature of seeds exceeds including some degree of heat damage at over specific temperatures (Shrestha et al., 2013b).

Table 2.4: Germination of canola seeds heated to various final temperatures using 3 kW, 5 kW, and 7 kW 50-ohm radio frequency heating.

Power (kW)	**Final temperature (°C)**	**Initial number of canola seeds**	**Number of germinated seeds after 7 days**
No treatment	4 (Stored, no treatment)	$_{a}10.0\pm0.0^{a}$	$_{d}9.6\pm0.5^{a}$
3	50	$_{a}10.0\pm0.0^{b}$	$_{c}9.3\pm0.5^{a}$
3	55	$_{a}10.0\pm0.0^{b}$	$_{c}9.3\pm0.5^{a}$
3	60	$_{a}10.0\pm0.0^{a}$	$_{e}10.0\pm0.0^{a}$
3	65	$_{a}10.0\pm0.0^{b}$	$_{b}9.0\pm0.0^{a}$
5	50	$_{a}10.0\pm0.0^{b}$	$_{c}9.3\pm0.5^{a}$
5	55	$_{a}10.0\pm0.0^{b}$	$_{c}9.3\pm0.5^{a}$
5	60	$_{a}10.0\pm0.0^{b}$	$_{d}9.6\pm0.5^{a}$
5	65	$_{a}10.0\pm0.0^{b}$	$_{a}8.6\pm0.5^{a}$
7	50	$_{a}10.0\pm0.0^{b}$	$_{c}9.3\pm0.5^{a}$
7	55	$_{a}10.0\pm0.0^{b}$	$_{c}9.3\pm0.5^{a}$
7	60	$_{a}10.0\pm0.0^{a}$	$_{e}10.0\pm0.0^{a}$
7	65	$_{a}10.0\pm0.0^{b}$	$_{a}8.6\pm0.5^{a}$

Note: Each mean represents the average of three replicates and represented as mean ± σ. Different subscripted alphabets in the same column indicate statistically significant ($p < 0.05$) according to Tukey HSD test. Different superscripted alphabets in the same rows (only Initial number of canola seeds and Number of germinated seeds after 7 days) indicate statistically significant ($p < 0.05$) according to Tukey HSD test.

2.6.3.3 Colour test

Table 2.5 shows L*, a* and b* values of stored and RF heated canola seeds up to various final temperatures(50°C, 55°C, 60°C, and 65°C) and cooling them down to the room temperature, at different power levels (3 kW, 5 kW, and 7 kW) using 50 ohm RF heating. The L* value which represents lightness reduced significantly with the increase in RF treatment temperature in all the power levels. The a* value which represents red vs green scale seems to reduce significantly with the increase in RF treatment temperature in all power levels except at 65°C at 5 kW and 7 kW. The b* value, which represents yellow vs blue scale, the scale also reduced significantly with the increase in treatment RF temperature. Thus, proving that RF heating has a significant influence on the colour of the canola seeds and further investigation for the actual reason for the changes is recommended.

Table 2.5: L*, a*, b*, ΔL*, Δa* and Δb* values of canola seeds at various final temperatures and various power levels 50-ohm radio frequency heating.

Power (kW)	Temperature (°C)	L*	a*	b*	ΔL*	Δa*	Δb*
No treatment	22	$_{h}$26.86±0.02	$_{i}$3.68±0.00	$_{l}$2.05±0.00			
3 kW	50	$_{i}$26.90±0.01	$_{b}$2.45±0.01	$_{d}$0.67±0.01	$_{c}$0.04±0.01	$_{i}$1.23±0.01	$_{i}$1.38±0.01
	55	$_{f}$26.43±0.01	$_{f}$3.26±0.01	$_{e}$0.80±0.01	$_{f}$0.43±0.01	$_{e}$0.42±0.01	$_{h}$1.25±0.01
	60	$_{f}$26.51±0.01	$_{c}$2.59±0.00	$_{b}$0.33±0.01	$_{e}$0.35±0.01	$_{h}$1.09±0.00	$_{k}$1.72±0.01
	65	$_{d}$26.33±0.01	$_{a}$1.91±0.01	$_{a}$-0.19±0.01	$_{g}$0.53±0.01	$_{j}$1.77±0.01	$_{l}$2.24±0.01

5 kW	50	$_{hi}$26.87±0.01	$_{d}$2.91±0.00	$_{c}$0.53±0.00	$_{a}$0.01±0.01	$_{g}$0.77±0.00	$_{j}$1.52±0.00
	55	$_{d}$26.07±0.01	$_{g}$3.40±0.01	$_{i}$1.18±0.03	$_{i}$0.79±0.01	$_{d}$0.28±0.01	$_{d}$0.87±0.03
	60	$_{g}$26.67±0.01	$_{g}$3.38±0.01	$_{j}$1.26±0.01	$_{d}$0.19±0.01	$_{d}$0.30±0.01	$_{c}$0.79±0.01
	65	$_{b}$25.76±0.01	$_{j}$3.71±0.01	$_{j}$1.28±0.01	$_{j}$1.10±0.01	$_{b}$-0.03±0.01	$_{b}$0.77±0.01
7 kW	50	$_{e}$26.31±0.01	$_{e}$3.18±0.01	$_{f}$0.83±0.00	$_{h}$0.55±0.01	$_{f}$0.50±0.01	$_{g}$1.22±0.00
	55	$_{d}$26.07±0.01	$_{g}$3.39±0.01	$_{g}$1.00±0.00	$_{i}$0.79±0.01	$_{d}$0.29±0.01	$_{f}$1.05±0.00
	60	$_{c}$25.83±0.01	$_{h}$3.61±0.00	$_{h}$1.06±0.01	$_{b}$0.03±0.01	$_{c}$0.07±0.00	$_{e}$0.99±0.01
	65	$_{a}$25.48±0.00	$_{k}$3.94±0.02	$_{k}$1.37±0.00	$_{k}$1.38±0.02	$_{a}$-0.26±0.02	$_{a}$0.68±0.00

Note: Each mean represents the average of three replicates and represented as mean ± σ. Different subscripted alphabets in the same column indicate statistically significant ($p < 0.05$) according to Tukey HSD test.

2.6.3.4 Oil quality analysis

Table 2.6 shows the PV, AV, and TOTOX value of canola oil at various final temperatures using 3 kW, 5 kW, and 7 kW 50-ohm RF heating. The PV, AV, and TOTOX values varied between 1.19 meq O^2 kg^{-1} and 1.80 meq O^2 kg^{-1}, 0.33 and 0.38, and 3.69 and 5.11 respectively. With the increase in treatment temperature and RF power levels the PV, AV, and TOTOX values increased significantly (Table 2.6). The measured values of PV, AV, and TOTOX values are in good agreement with those reported by Mohammadi et al. (2013) and Tynek et al. (2012), but slightly higher than the values reported by Yu et al. (2016b). When the canola seeds were RF heated to 65 °C at 7 kW, the highest PV value was 1.8 meq O^2 kg^{-1}. The values seem to be a little higher than those published by Yu et al. (2016). Regarding the AV value, the results published by Yu et al. (2016) and Tynek et al. (2012) were lower than the ones shown in this chapter, which could be caused by the presence of prooxidants such as iron and copper (Tynek et al. 2012). The highest AV was 1.51 meq O^2 kg^{-1} and the lowest 1.313 meq O^2 kg^{-1} at a final temperature of 65°C at 5 kW and 50°C at 3 kW, respectively. The PV and AV equally influenced the level of TOTOX value, showing levels of both primary and secondary oxidation of canola oil. Both PV, AV, and TOTOX values increased significantly with temperature and power (Table 2.6). Therefore, the qualities of the oil extracted from the RF treated canola seeds gradually degrade as temperature and power level increases.

Table 2.6: Peroxide value, p-anisidine value and total oxidation value of canola oil at various final temperatures using 3 kW, 5 kW, and 7 kW 50-ohm radio frequency heating.

Power (kW)	Temperature (°C)	Peroxide value	p-anisidine value	Total oxidation value
No treatment	4 (stored, no treatment)	$_{a}$1.19±0.47	$_{a}$1.31±0.38	$_{a}$3.69±0.42
3	50	$_{c}$1.37±0.02	$_{b}$1.36±0.04	$_{c}$4.12±0.02
3	55	$_{d}$1.51±0.10	$_{de}$1.41±0.03	$_{e}$4.44±0.17
3	60	$_{e}$1.62±0.02	$_{de}$1.41±0.03	$_{h}$4.66±0.05
3	65	$_{f}$1.79±0.02	$_{f}$1.49±0.05	$_{i}$5.09±0.09
5	50	$_{b}$1.31±0.01	$_{c}$1.38±0.07	$_{b}$4.02±0.07
5	55	$_{d}$1.50±0.05	$_{e}$1.42±0.01	$_{e}$4.43±0.04
5	60	$_{e}$1.58±0.06	$_{e}$1.42±0.00	$_{g}$4.59±0.11
5	65	$_{f}$1.80±0.02	$_{e}$1.51±0.03	$_{i}$5.11±0.07
7	50	$_{c}$1.39±0.02	$_{cd}$1.39±0.19	$_{d}$4.17±0.10
7	55	$_{d}$1.52±0.29	$_{e}$1.43±0.10	$_{f}$4.47±0.19
7	60	$_{e}$1.60±0.48	$_{e}$1.43±0.11	$_{g}$4.58±0.29
7	65	$_{f}$1.80±0.24	$_{f}$1.50±0.49	$_{i}$5.1±0.36

Note: Each mean represents the average of three replicates and represented as mean ± σ. Different subscripted alphabets in the same column indicate statistically significant ($p < 0.05$) according to Tukey HSD test.

2.7 Conclusions

The 50-ohm RF heating system used in this research caused non-uniform temperature distribution during the treatment of bulk canola seeds of identical MC were treated. The hottest and the coldest spots were found adjacent to the hot electrode and the cold electrode respectively at every RF power levels. Thus, proving that non-uniform temperature distribution is consistently observed during the 50-ohm RF treatment of identical canola seeds samples irrespective of the power level. A comparable heating pattern might be observed while heating other biological samples with similar or identical physicochemical properties to that of the canola seeds used in this research using a 50-ohm RF heating system/applicator. Thus, it is strongly recommended to extensively study the heating characteristics of an RF heating system before implementing it in the grain processing industries, so supplementary technologies can be developed to avoid the non-uniform temperature distribution during the RF heating process. Also, quality parameters of the canola seeds were affected by the RF treatment, significant changes in MC, germination rate, colour, and oil quality (oxidation) of the canola seeds were observed after the RF treatment. Application of RF heating is promising in agriculturally based unit operations such as disinfestation and drying of grains, meat thawing, and any heating applications in food and agricultural industries. As RF heating provides selective and volumetric heating and faster heating rates compared to other commercially available technologies, however the physicochemical properties of the agricultural commodities are affected under intensive heating conditions. Therefore, RF power level, treatment temperature, and supplementary technologies to avoid non-uniform temperature distribution should be considered in implementing a 50-ohm RF heating system in oilseeds or grains industries where the physicochemical properties of the commodity play a crucial role.

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2.9 References

Alfaifi, B., J. Tang, Y. Jiao, S. Wang, B. Rasco, S. Jiao and S. Sablani. 2014. Radio frequency disinfestation treatments for dried fruit: model development and validation. *Journal of Food Engineering*, 120:268–276.

AOCS. 1993. Official methods and recommended practices of the American oil chemists' society. Methods: Cd 8-53, Cd 18-90, Cd 1-25, 4th edition.

ASAE. 2002. ASAE S352.2, moisture measurements e unground grains and seeds. In *ASAE standards*. St. Joseph, MI: ASAE.

Birla, S. L., S. Wang and J. Tang. 2008a. Computer simulation of radio frequency heating of model fruit immersed in water. *Journal of Food Engineering,* 84(2):270-280.

Birla, S. L., S. Wang, J. Tang and G. Tiwari. 2008b. Characterization of radio frequency heating of fresh fruits influenced by dielectric properties. *Journal of Food Engineering*, 89(4):390-398.

Canola Council of Canada. 2019. https://www.canolacouncil.org/markets-stats/industry-overview/ (2019/05/18).

Canola Watch. 2015. http://www.canolawatch.org/2011/05/09/estimating-flea-beetle-damage-in-canola/ (2019/05/18).

Coaxial Power System Ltd. 2018. https://www.coaxialpower.com/rf-matching-networks-tuners.html (2019/05/18).

Dabbak, S. Z. A., H. A. Illias, B. C. Ang, N. A. A. Latiff and M. Z. H. Makmud. 2018. Electrical properties of polyethylene/polypropylene compounds of high-voltage insulation. *Energies*, 11(1448):1-13.

Gao, M., J. Tang, Y. Wang, J. Powers and S. Wang. 2010. Almond quality as influenced by radio frequency heat treatments for disinfestation. *Postharvest Biology and Technology*, 58(3):225-231.

Hou, L., B. Ling and S. Wang. 2014. Development of thermal treatment protocol for disinfesting chestnuts using radio frequency energy. *Postharvest Biology and Technology,* 98:65-71.

Huang, Z., F. Marra, F and S. Wang. 2016. A novel strategy for improving radio frequency heating uniformity of dry food products using computational modeling. *Innovative Food Science and Emerging Technologies,* 34:100–111.

Huang, Z., F. Marra, J. Subbiah and S. Wang. 2018. Computer simulation for improving radio frequency (RF) heating uniformity of food products: A review. *Critical Reviews in Food Science and Nutrition,* 58(6):1033-1057.

Jiao, S., J. A. Johnson, J. Tang, G. Tiwari and S. Wang. 2011. Dielectric properties of cowpea weevil, black-eyed peas and mung beans with respect to the development of radio frequency heat treatments. *Biosystems Engineering,* 108(3):280-291.

Jiao, S., Y. Deng, Y. Zhong, D. Wang and Y. Zhao. 2015. Investigation of radio frequency heating uniformity of wheat kernels by using the developed computer simulation model. *Food Research International*, 71:41–49.

Jones, P. L. and A. T. Rowley. 1996. Dielectric drying. Drying Technology, 14:1063–1098.

Llave, Y., S. Liu, M. Fukuoka and N. Sakai. 2015. Computer simulation of radiofrequency defrosting of frozen foods. *Journal of Food Engineering* 152:32–42.

Luechapattanaporn, K., Y. Wang, J. Wang, M. Al-Holy, D. H. Kang, J. Tang and L. M. Hallberg. 2004. Microbial safety in radio frequency processing of packaged foods. *Journal of Food Science,* 69:201–206.

Marra, F., L. Zhang and J. G. Lyng. 2009. Radio frequency treatment of foods: review of recent advances. *Journal of Food Engineering*, 91:497–508.

Mitcham, E. J., R. H. Veltman, X. Feng, E. De Castro, J. A. Johnson, T. L. Simpson et al. 2004. Application of radio frequency treatments to control insects in in-shell walnuts. *Postharvest Biology and Technology*, 33(1):93-100.

Mohammadi, M., P. Hajeb, R. Seyyedian, H. M. Gholam and A. Barmak. 2013. Evaluation of oxidative quality parameters in imported edible oils in Iran. *British Food Journal* 115(6):789-795.

National Aeronautics and Space Administration. 2020. https://imagine.gsfc.nasa.gov/resources/dict_qz.html#radio (2020/01/02).

Neter, J., M. Kutner, W. Wasserman and C. Nachtsheim. 1996. Applied linear statistical models, 4th edition. New York: McGraw-Hill/Irwin.

Romano, V. and F. Mara. 2008. A numerical analysis of radio frequency heating of regular shaped food stuff. *Journal of Food Engineering*, 84(3):449-457.

Shrestha, B. L. and O. D. Baik, 2013a. Radio frequency selective heating of stored-grain insects at 27.12 MHz: A feasibility study. *Biosystems Engineering* 114(3):195-204.

Shrestha, B. L., D. Yu and O. D. Baik. 2013b. Elimination of *Cryptolestes ferrugineus* S. in wheat by radio frequency dielectric heating at different moisture contents. *Progress in Electromagnetics Research*, 139:517-538.

Sutherland, J. W. and T. F. Ghaly. 1982. Heated air drying of oilseeds. *Journal of Stored Products Research*, 18(2):43-54.

Tiwari, G., S. Wang, J. Tang and S. L. Birla. 2011. Analysis of radio frequency (RF) power distribution in dry food materials. *Journal of Food Engineering*, 104(4):548-556.

Tynek, M., R. Pawlowicz, J. Gromadzka, R. Tylingo, W. Wardencki and G. Karloyits. 2012. Virgin rapeseed oils obtained from different rape varieties by cold pressed method – their characteristics, properties, and differences. *European Journal of Lipid Science and Technology*, 114:357–366.

USDA Foreign Agricultural Service. 2015. Production, Supply and Distribution Online Database, query for Commodity: "Oilseed, Rapeseed"; Data Type: "Production"; Country: "All countries"; Year: "2018", https://www.fas.usda.gov/commodities/other-oilseeds (2019/05/18).

Wang, S., M. Monzon, J. Johnson, E. Mitcham and J. Tang. 2007. Industrial-scale radio frequency treatments for insect control in walnuts: I: Heating uniformity and energy efficiency. *Postharvest Biology and Technology,* 45(2):240-246.

Wang, Y., Y. Li, S. Wang, L. Zhang, M. Gao and J. Tang. 2011. Review of Dielectric Drying of Foods and Agricultural Products. *International Journal of Agricultural and Biological Engineering*, 4(1):1–19.

Yang, H. W. and S. Gunasekaran. 2001. Temperature profiles in a cylindrical model food during pulsed microwave heating. *Journal of Food Science,* 66(7):998-1004.

Yu, D., B. L. Shrestha and Baik, O. D. 2015. Radio frequency dielectric properties of bulk canola seeds under different temperatures, moisture contents, and frequencies for feasibility of radio frequency disinfestation. *International Journal of Food Properties*, 18(12):2746-2763.

Yu, D., B. L. Shrestha and O. D. Baik. 2016a. Temperature distribution in a packed bed of canola seeds with various moisture contents and bulk volumes during radio frequency (RF) heating. *Biosystems Engineering*, 148:55-67.

Yu, D., B. L. Shrestha and O. D. Baik. 2016b. Radio frequency (RF) control of red flour beetle (*Tribolium castaneum*) in stored rapeseeds (*Brassica napus* L.). *Biosystems Engineering*, 151:248-260.

CHAPTER 3

Thermal death kinetics of *Tribolium castaneum* in stored *Brassica napus L.* seeds using a pilot-scale 50-ohm radio frequency heating system

Contribution of this chapter on overall study

The determination of thermal death kinetics of red flour beetle in stored canola seeds using a pilot-scale 50-ohm radio frequency heating system is important to know the selectivity of the dielectric heating system. In this chapter the mortality of the adult insects was determined experimentally at various temperatures and power levels. The mortality of the insects was used to determine the thermal death kinetics parameters by reverse simulation method. These parameters are critical for designing an effective radio frequency heating protocol for disinfestation of insect pests in stored grains. All the experiments in this chapter were conducted and the journal paper manuscript was drafted by me.

3.1. Abstract

Adult red flour beetles (*Tribolium castaneum*) infesting canola seeds (*Brassica napus* L.) at 9% moisture content (MC) were treated using a 50-ohm radio frequency (RF) heating system and

thermal mortalities of the insect pests were determined. The infested seeds were treated between 297 K and 338 K at RF heating power of 3 kW, 5 kW, and 7 kW. At 7 kW 100% of the insects were killed at the end temperature of 338 K, at 5 kW more than 95% of the insects, and at 3 kW more than 80% of the insects were killed. The RF exposure times to achieve end temperature from 297 K to 338 K were, 334 to 448 s, 172 to 242 s and 122 s to 170 s for the samples, treated at 3 kW, 5 kW, and 7 kW respectively. The survival rate of the adult *T. castaneum* decreased with an increase in temperature (297 K to 338 K) and increase in RF power levels (3 kW to 7 kW). Desirable selective heating effect on mortality was more predominant at higher RF powers. An inverse simulation was used to estimate kinetic parameters of the thermal death of the adult *T. castaneum*. 4^{th} order Runge-Kutta method was used to solve the ordinary differential equation (ODE) based kinetic model which has an Arrhenius temperature-dependent reaction rate constant. The thermal death kinetics of the adult *T. castaneum* followed 1^{st} order reaction with the activation energy of 97.50 kJ/mol. Satisfactory agreements were observed between the mortalities predicted using the kinetic model and the experiments.

3.2 Nomenclature

MC moisture content (%)

RF radio frequency

RFG radio frequency generator

AMN automatic matching network

t heating time (s)

N number of live insects at a given time

N_0 initial number of the insects

k reaction rate constant (1/s)

n order of the reaction

k_0 frequency factor

E_a activation energy (J/mol)

R universal gas constant (8.314 J/mol·K)

T temperature of the bulk canola seeds (K)

df degree of freedom

RMSE root mean square error

LT lethal time (s)

3.3 Introduction

Total production of canola seeds in 2018 - 2019 was 72.80 million metric tons and in 2019-2020 is expected to be 74.80 million metric tons where, some of the major canola producing countries include China, India, Canada, and European Union (USDA Foreign Agricultural Service, 2019). Over 90% of the canola produced in Canada is exported to markets around the world. In 2017, according to the Canola Council of Canada, Canadian grown canola contributed $26.7 billion to the Canadian economy each year, including more than 250,000 Canadian jobs and $11.2 billion in wages. (Canola Council of Canada, 2017). In Canada, the losses of oilseed production average out 8 to 10% in annual crop yield due to insect pests causing over multimillion dollars loss in the Canadian economy (Canola Watch, 2015). Along with economic losses, insect pest infestations are a huge barrier to exportation of the grains (Gao et al., 2010). The trade regulations of domestic and international markets have made postharvest treatments of all kinds of food products mandatory to ensure quarantine security from insect pests (Birla et al., 2008; Jiao et al., 2011).

According to Sinha and Watters (1985), *T. castaneum* is commonly found in stored grains and oilseeds all over the world. In addition, according to Canola Watch, the primary insects in stored canola include *C. ferrugineus* (Stephens), *T. castaneum* and *O. surinamensis* are found in stored canola if cereal grain or weed seeds are mixed in with the canola (Canola Watch, 2019). Disinfestation through fumigation using MBr has been widely used and was rather a convenient method for disinfestation of stored agricultural commodities (Sinha and Watters, 1985). Nevertheless, the use of MBr was prohibited since Montreal Protocol because of the health hazards caused by excessive insecticide residues and the damaging effect on the ozone layer (Birla et al., 2008; Griffin, 1988; Wang et al., 2004). Apart from the chemical disinfestation processes, thermal disinfestation processes are effective, so the knowledge of the thermal death kinetics of insect pests is crucial to develop an efficient thermal disinfestation protocol for agricultural commodities (Wang et al., 2007).

Radio Frequency (RF) heating happens to be an emerging technology in the field of disinfestation in stored grains. RF heating is centered on electromagnetic radiation, so RF heating follows the dielectric heating pattern. Volumetric and selective heating happens to be major advantages of dielectric heating. Although the physical properties, specific heat, and bulk density of the insects and the grains are different, the power dissipation boosts a higher temperature increment rate in insects relating to that of the grains (Shrestha et al., 2013b). Therefore, RF heating is predicted to kill insect pests without hampering the physiochemical properties of the grains significantly (Tang et al., 2000). Some, other nonchemical treatments to control insect pests include ionizing radiation, hot air, and cold storage, however, these techniques require a longer treatment time and a substantial capital investment and may sometimes leave live insect pests after the treatments (Heather and Hallman 2008; Want et al., 2004).

Lagunas-Solar et al., (2007) reported the mortalities of *S. cerealella* (Olivier) and *R. dominica* (Fabricius) in rice using RF heating. A mortality of 99% of *S. cerealella* was achieved at 55℃ to 60°C for 5 min of heating, and 100% mortality of *R. dominica* at 60°C for 1 h of heating. There were no significant changes in moisture level and milling quality of the rice. Shrestha et al. (2013a) have achieved 100% mortality for all the life stages of *C. ferrugineus* (Stephens) in stored wheat at 60°C with RF heating (1.5 kW, 27.12 MHz) without significant degradation of the wheat qualities. Since, this research is based on thermal treatment of *T. castaneum* in stored canola using RF heating, understanding the thermal kinetic model for the mortality of *T. castaneum* is crucial. Literature shows numerous kinetic models intended for the mortalities of insect pests using thermal processing. Tang et al. (2000) validated a possibility of applying high temperature and short time thermal treatments to control larvae of *C. pomenella* (Linnaeus) with a minimal thermal impact on fruit quality using the thermal death kinetics of the insect. Wang et al., (2002a) reported thermal death kinetic parameters for the fifth-instar *C. pomenella*, which were heated to four temperatures (46℃, 48℃, 50℃, and 52°C) using a heating block system. The thermal death kinetics of the insects followed a 0.5^{th} order reaction with an activation energy of 472 kJ/mol at a heating rate of 18°C/min. Johnson et al., (2003) estimated the lethal exposure times for the fifth-instar larvae of Indian meal moth, *P. interpunctella* (Hubner) at 44℃ to 52°C during RF heating using a 0.5^{th} order kinetics model. They obtained the RF heating time of less than 5 min to achieve 95% mortalities at 50℃ and 52°C. A thermal death kinetic model of *T. castaneum* at larvae stage (the most heat - tolerant life stage of the insect) with 0.5^{th} order reaction was developed to estimate lethal exposure times at 48°C, 50°C, and 52°C during RF heating (Johnson et al., 2004). They reported the lethal times (LTs) to achieve 99% mortalities were 1.6min, 9.1min, and 76.8 min at the holding temperatures of 52°C, 50°C, and 48°C, respectively. Similarly, Yu et al., (2017) studied, thermal mortalities of adult *T. castaneum* infesting canola seeds using various MCs, volumes, and temperature using a lab scale (1.5 kW) conventional, 27.12 MHz RF system and found that the thermal death kinetics followed 1st order reaction with the activation energy of 100 kJ / mol. Literature shows limited evidences of the application of high power 50-ohm RF heating system in agricultural products processing. Since the heating characteristics of RF heating supports the process of disinfestation of insects in stored agricultural commodities (selective heating). Thus, the study was carried out to understand the selective heating efficiency of a 50-ohm RF heating system with a tubular type housing and parallel plate electrodes at different power levels during disinfestation of *T. castaneum* in stored canola seeds.

The objective of this chapter is to determine kinetic parameters for the thermal death of adult *T. castaneum* in stored canola during 50-ohm RF disinfestation based on the temperature history of the stored canola. This involved the investigation of the immediate mortality of adult *T. castaneum* in stored canola, at 9% MCs and end temperatures of the host grains during RF heating at 3 kW, 5 kW, and 7 kW at 27.12 MHz. Thermal death kinetics of the adult *T. castaneum* based on the immediately determined mortalities and temperature histories of the host material (canola seeds) will be helpful. The determined kinetic parameters and model can predict mortalities at specific RF heating times without knowing insect body temperatures. They can be also used to determine proper RF heating conditions for disinfestation of the adult *T. castaneum*. Therefore, in this study, the thermal death kinetics of the adult *T. castaneum* infesting canola seeds at a constant MC of seeds at various power levels were characterized based on dynamic temperature changes of the canola seeds and the experimental data of insect mortalities during RF heating.

3.4 Materials and methods

3.4.1 The radio frequency system

The RF system consists of the 15 kW 27.12 MHz RF generator (Coaxial Power Systems Ltd. RFG 15K-27) and matching network (Coaxial Power Systems Ltd. AMN15KR) both manufactured by Coaxial Power System Ltd. which is then connected to an applicator which was designed and fabrication process by Engineering Shop, College of Engineering, University of Saskatchewan.

The 15 kW 27.12 MHz radio frequency generator (RFG) (Figure 3.1): According to Coaxial Power System Ltd. the RFG was designed to drive a specific characteristic impedance, 50-ohms. The characteristic impedance of the output cable and allowed the generator to deliver full power at maximum efficiency. If the output impedance varied from 50 ohm the protection circuits in the RFG reduce the output power in order to protect the RFG from overload. Except for dummy loads and some types of antenna most real-world loads differed substantially from 50-ohm and a device was needed to transform the output of the RFG to the actual load impedance of the system being driven. It was sometimes possible to use a conventional wound transformer, but most often the matching device was made up of a network of series and parallel impedances that combine to perform the transformation, i.e. a 'matching network'.

Figure 3.1: Radio frequency generator (Manufactured by Coaxial Power Systems Ltd., UK)

RF Impedances: The impedance of an application was rarely pure resistance, often it consisted of a combination of resistance and capacitance. That can be considered as an 'equivalent circuit' consisting of a resistor and capacitor. Two forms of circuit exist, series and parallel. It was important to realize that neither form is correct or incorrect, both have validity, nor it is possible to represent the output in whichever form is most convenient. The parallel form represents a load as a resistor and capacitor in parallel. The series form represented a load like a resistor and capacitor in series. The resistor would typically be low in value.

Matching network: Coaxial Power Systems Ltd manufactures two styles of impedance matching network to link the load to the RF generator. The purpose of the network was to adjust the input impedance of the load to 50-ohms so that maximum power was transferred from the generator, whose output impedance is 50-ohms, to the load. The network was installed as close as possible to the load. The best possible position, in a plasma application, for example, would be to mount the network directly on the vacuum chamber with a direct connection to the electrode or magnetron. Coaxial Power Systems Ltd. manufactures two types of network - manual and automatic.

Figure 3.2: Automatic matching network (Coaxial Power Systems Ltd.)

The automatic matching network (AMN) was like the manual version except that servomotors drive the capacitors. At the input of the network, a phase and magnitude detector determine the position of the capacitors. This information was transferred to the separate controller. The controller then drives the servomotors to the positions, which gave zero, or minimum reflected power. The controller is ½ rack, 4U high and is usually fitted in the same enclosure as the generator. Alternatively, the controller may be fitted within a generator - the readouts and controls on the generator front panel. The position of each variable capacitor was shown on a 31/2-digit LED meter. Automatic or manual mode switch was selectable - in manual mode, the servomotors are controlled by spring-loaded switches. The start position of the capacitors can be individually adjusted. When RF power is detected, the capacitors automatically adjust for minimum reflected power. When the RF is turned off, the motors drive the capacitors back to the original position. The start positions are adjusted using potentiometers accessible via the controller front panel. (Coaxial Power System Ltd. 2018).

3.4.2 Applicator

The applicator had parallel plate electrodes (hot and ground) which were used in this study because of its uniform electric field strengths from beginning to end of the electrode. In between the two electrodes was the tubular channel, made of polypropylene; diameter of 30 cm and length of 70 cm. The gap size between the two electrodes was 36 cm as shown in Figure 3.3. The samples consisting of insects and canola grains were loaded in the channel which acted as an insulator during the RF heating process, where, the insects were killed, and the canola grains being heated.

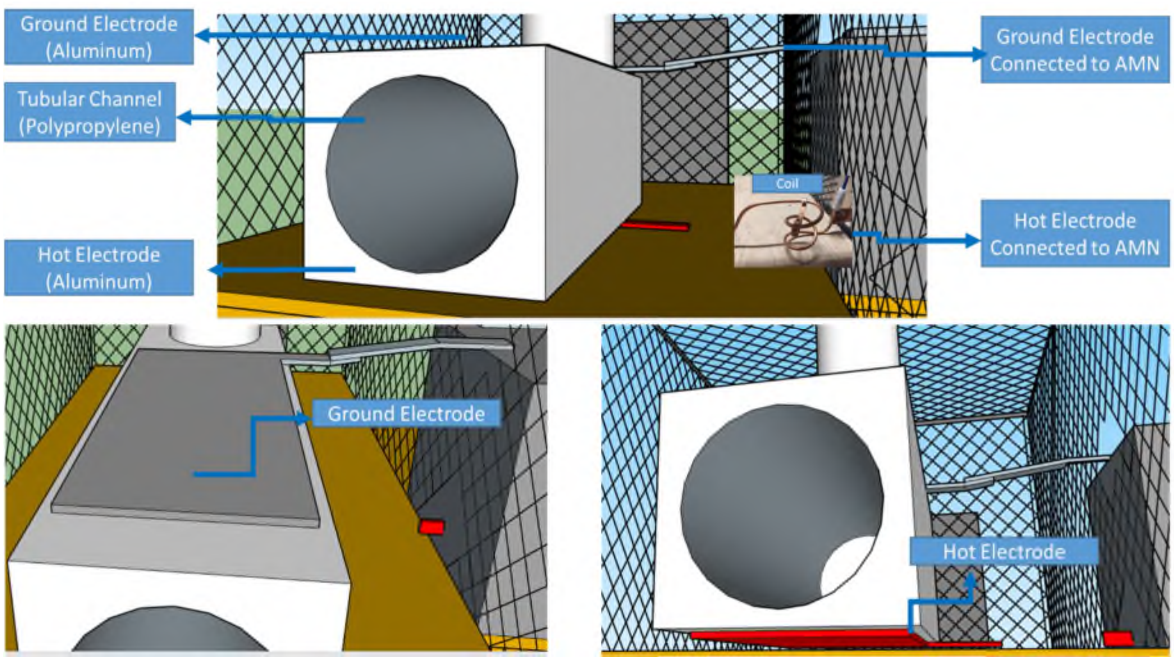


Figure 3.3: Applicator designed and fabricated by Engineering Shop, College of Engineering, and University of Saskatchewan.

3.4.3 Canola seed samples

The samples were provided by Viterra Inc., Saskatoon, Canada at various moisture levels (6%, 7%, and 9%) from which 9% MC (w.b) was prepared from canola seeds. The seeds were cleaned and stored in polypropylene boxes at 4°C for maximum of six months before using them. The MC of the seeds was calculated from the difference in water loss by drying 10 g of canola seeds in a hot air oven (Despatch, Despatch Industries, MN, USA) for 24 h at 103°C (ASAE, 2002; Brusewitz, 1975). Based on the MC of the canola seeds, 9% MC samples were prepared by mixing the required amount of distilled water. The required amount of distilled water was calculated based on the mass and the MC of the canola samples. During the addition of distilled water, the seeds contained in the boxes were continuously shaken to ensure even distribution of water. The boxes were kept at room temperature (24°C) for 3 days, and during that period the boxes were shaken periodically. After 3 days the MC was measured and the process was repeated until equilibrium MC of 9% MC (±0.2%) was achieved, then was followed by storage in a 4°C cold storage chamber until used. The samples for experiments were taken out from the cold storage chamber and could raise their temperature to room temperature.

3.4.4 Insect culture

The insects were cultured using the process described by Shrestha et al., (2013a) and Yu et al. (2016). The adult red flour beetles (*T. castaneum*) were acquired from Agriculture and Agri-Food Canada at the University of Manitoba, Canada. The insects were reared in a mixture of wheat kernels (14% MC) and wheat germs in a proportion of 70% to 30% by weight. 200 total adult insects were divided into 2 glass jars (2 L), 100 insects in each jar and mixed with 1.5 kg of the rearing mixture in each jar. The jars were ventilated by using a lid with fabric. The cultures could grow in a temperature and humidity chamber maintained at 25°C and 70% RH. These cultures were used to prepare another batch of new cultures after 10 weeks. The insects with the rearing mixture were separated using the Canadian standard sieve #40 assembled with the bottom tray. Then insects were sucked through a suction pipe into a glass vial which was closed with a # 5 rubber cap with two holes, one connected to the suction pipe, and the other to the vacuum device with the rubber tube. The hole connecting to the vacuum was covered with a fine wire net on an inner side of the collecting vial to stop the insects sucking away from the vial.

3.4.5 Radio frequency exposure time of the canola seeds

A Reflex™ signal conditioner and the fiber optic temperature sensors with an accuracy of ±0.8°C (Neoptix, Québec City, Québec, Canada) were used to measure and monitor the temperatures of samples. A dedicated LabVIEW (2010v.10) program was developed to interface with the data acquisition device connected to the temperature sensors. The temperatures of the sample were displayed and recorded every 2 s. RF exposure times (s) of the canola seeds were determined when the temperature of the hottest spot of the bulk seeds reached up to each desired temperature (338 K) from 297 K (initial temperature) for 9% MC of the seeds (Figure 3.5). 27 kg of canola seeds were measured and packed tightly in 7 polypropylene bags with dimension of 70 cm in length and 30 cm in diameter (Figure 3.4). In the process, it was made sure that the bags are packed tightly and uniform by dividing the weight equally. The temperature histories of the canola seeds at 9% MC were measured at three different power levels (3 kW, 5 kW, and 7 kW), then, regression models were developed for the temperature (K) of the seeds as a function of RF exposure time (s) for input data in the kinetic model used in this study. During the temperature measurement, the sensor was placed at the hottest spot of the canola samples. It does not matter whether the hottest or coldest spot was used as we just needed different sets of temperature vs time and corresponding experimental mortalities to determine kinetic parameters using inverse simulation. The determination of the hottest spot was done through heating distribution experiments. From the heating distribution experiment, it was found that the front bottom side of the applicator generated the hottest spot. The identification of the hottest spot was done by studying the temperature distribution in the bulk canola seeds in the tubular applicator at different RF power levels, which is not elaborated in this chapter. So, from the study insects were in the hottest spot in a polypropylene bag mixed well with the canola grains. The average of triplicate measurements was used for the RF exposure time (s) of the seeds.

3.4.6 Insect mortality

The insect mortalities were determined by introducing the adult insects in a polypropylene bag (5

(a) (b) (c)

Figure 3.4: (a) Polypropylene bag with canola samples, dimension of 70 cm in length and 30 cm in diameter (b) Fiber optic temperature sensors placed inside polypropylene bag with canola samples (c) 7 polypropylene bag with canola samples stacked inside the applicator.

cm in length and 10 cm in diameter). A total of 20 adult insects (70-72 days old from the time of hatching from eggs) were introduced along with the canola grains, at the hottest spot. The portion with the highest heating rate in the bulk canola seeds during the RF treatment was chosen to show the effectiveness of killing insects with optimally designed RF heating systems. The infested canola seeds were heated until the hottest spot of the bulk seeds reached up to the each desired (end) temperature (323 K, 328 K, 333 K, and 338 K) from 297 K (initial temperature) at each power level (3 kW, 5 kW, and 7 kW). The dead and the live insects were counted to calculate mortalities. The immediate mortalities of the adult *T. castaneum* at each desired temperature were tested in triplicate and then averaged for each MC of the seeds.

3.4.7 Kinetic modeling

The thermal death rate of the adult *T. castaneum* was modeled using the following kinetic model.

$$\frac{d(N/N_0)}{dt} = -k(\frac{N}{N_0})^n \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.1)$$

Where, t is the heating time (s), N and N_0 are respectively the numbers of live insects at a time and the initial number of the insects, k is the reaction rate constant (s^{-1}), and n is the order of the reaction. The temperature-dependent reaction rate constant can be expressed using the Arrhenius relationship as follows:

$$k = k_0 \exp\left(\frac{E_a}{RT}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.2)$$

Where, k_0 is the frequency factor, E_a is the activation energy (J/mol), R is the universal gas constant (8.314 J/molK), and T is the temperature of the bulk canola seeds (K). k_0 and E_a for adult *T. castaneum* were estimated by inverse simulation which is based on experimental mortality data and transient temperature history, which is a combination of temperature-dependent reaction rate (variable coefficient) and 1st order reaction kinetics (ordinary differential equation). Thus, it should be solved numerically. In an ideal condition, to obtain kinetic responses of insects to heat treatment, maintaining temperature of insect body constant at different levels during the heating is necessary to use a conventional estimation method ($ln\ k \propto 1/T$) (Wang et al. 2007). By doing so, the cofounded effects of thermal lags during the heating of insect bodies (thermal disinfestation) are omitted. That means, in a practical situation temperature history of the insect bodies during any thermal process significantly differs from the ideal step-function temperatures assigned in the conventional estimation method (Wang et al. 2007). Thus, the method used in this chapter covers that transient period as well, which is more sophisticated than the conventional methods. Also, the thermal heating process used in this cahpter is based on high power RF fields. Because of selective heating in RF heating, the insect body temperature should be higher than the grain temperature (Shrestha and Baik, 2013b). This chapter also studies the efficiency of selective heating during disinfestation of canola seeds from adult *T. castaneum* using a 50-ohm RF system at different power levels and compares with other published works based on a similar estimation method under different dielectric heating conditions. Even, generation of constant holding temperatures of insect body with the RF heating is not possible.

The correlation between grain temperatures with kinetic parameters is crucial for practical purposes and comparison, as it is extremely difficult to measure insect body temperatures during the RF heating process due to their tiny size (3 - 4 mm) and mobility. Thus, transient temperature histories of the canola seeds during RF heating were used instead of those of the insects. This makes the activation energy and frequency factor as apparent or effective values. It is, however, assumed that the canola seeds had similar heating patterns as those of the insects even if their heating speed was slower. Using the temperature of the canola seeds instead of the insect-body temperature was the limitation of this study, however, at the same time, this approach would be more practical for real-world applications. Only limited mobility of the insects in the seed sample during the RF heating was observed due to the natural compactness of the tiny seeds (The diameter of the seed is approximately 1.8 mm).

Substitution of the value of *k* from Equation 3.2 into Equation 3.1 results in the thermal death rate of the adult *T. castaneum* as shown in Equation 3.3.

$$\frac{d(N/N_0)}{dt} = k_0 \exp\left(\frac{E_a}{RT}\right)(\frac{N}{N_0})^n \ldots\ldots\ldots\ldots\ldots..(3.3)$$

The ordinary differential equation, Equation 3.3 was solved using ODE 45 solver based on the 4th order Runge-Kutta method in MATLAB R2019a (The MathWorks Inc., Natick, MA, USA). The optimum values of k_0, E_a, and n were determined by minimizing the root mean square error (RMSE) between the values predicted from the kinetic model and the experimental data as depicted in Equation 3.4.

$$RMSE = \sqrt{\frac{1}{m}\sum_{i=1}^{m}(x_i - x_i')^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(3.4)$$

where, m is the population of the data, x_i is the experimental value, and x_i' is the value predicted using the kinetic model, Equation 3.3. The unknown parameters, k_0, E_a, and n were determined by trial and error from 3 different sets of time-temperature data (4 points per each set) depending on RF heating rates. The value of n was estimated to be from 1±0.01 to 2±0.01 with an interval of 0.2±0.01, we set the order of kinetics (n) as 1, 1.2, 1.4, 1.6, 1.8 and 2 for all the estimation. So, along with the value of n only the other two unknown parameters k_0, and E_a were estimated. The kinetic model was also used to estimate LTs to achieve 90% (LT_{90}) and 99% (LT_{99}) mortalities of the insects infesting the canola seeds at different power levels.

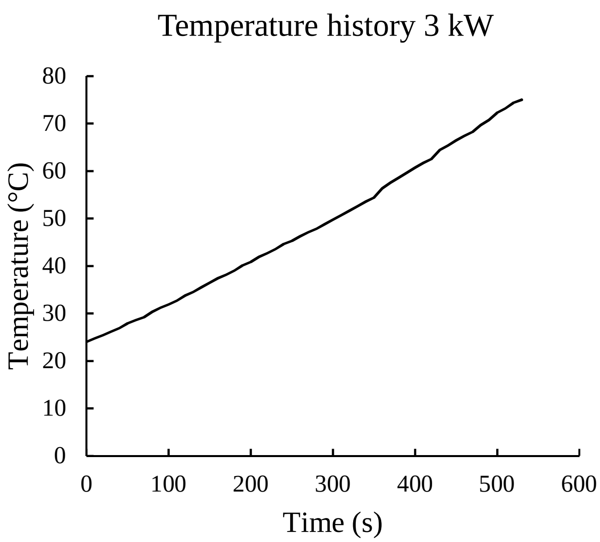
3.4.8 Statistical analysis

All experiments were done in triplicate. Excel (MSO 2016) was used to process and analyze data. The Analysis of Variance (ANOVA) was used to determine the statistical differences of the temperatures, power level, and immediate mortalities at 95% confidence interval (p -value< 0.05)

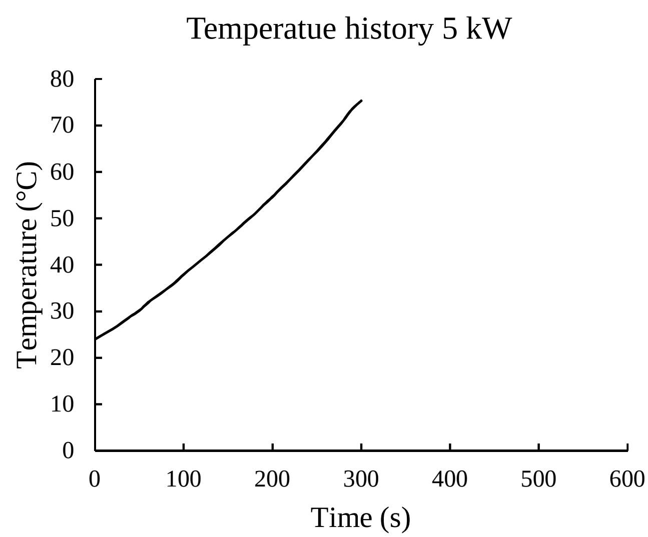
3.5 Results and discussion

3.5.1 Temperature histories of the canola seeds samples

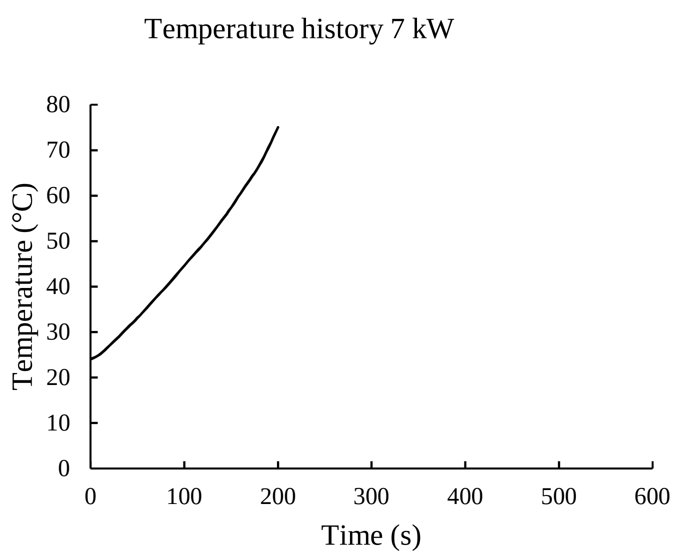
Figure 3.5 shows the temperature histories of the 9% MC canola seed samples at 3 kW, 5 kW, and 7 kW during RF heating.



(a)



(b)



(c)

Figure 3.5: The temperature histories of 9% moisture content (wet basis) canola samples at various power levels during the radio frequency heating (a) temperature history at 3 kW (b) temperature history at 5 kW (c) temperature history at 7 kW. (Note: The experimental data points relate to simple straight lines for visual presentation).

The rate of the temperature increment of the seeds was apparently proportional to the power levels of the RF heating. Similarly, the heating rate increased with power level while heating agricultural commodities, which include corn, barley, canola and wheat using microwaves. (Shivhare et al. 1992; Soysal 2004; Manickavasagan et al. 2006). Microwave heating pattern can be considered in this research as the principle of heating in both microwave and RF are based on electromagnetic (dielectric) heating principle. The RF exposure times to reach the end temperatures of canola samples at different power levels are presented in Table 3.1.

Table 3.1: The radio frequency average exposure times to reach the different end temperatures (338 K, 333 K, 328 K, 323 K) of 9% moisture content (wet basis) canola samples at different power levels.

Power (kW)	Time (s)			
	338 K	333 K	328 K	323 K
3	448±6	402±4	354±4	304±4
5	242±2	220±4	194±4	172±6
7	170±2	156±4	138±6	122±8

Note: Each mean represents the average of three replicates and represented as mean ± σ.

The regression models for the temperatures (K) of the canola seeds as a function of the RF exposure time (s) at the interested MCs for both the small and the large volume samples are listed in Table 3.2.

The regression models for the temperature of the canola grains as a function of RF heating time at different RF power levels: 3 kW in equation (3.5), 5 kW in equation (3.6), and 7 kW in equation (3.7), at 9% MC in Table 3.2.

Table 3.2: Regression models for the temperature of the canola seeds as a function of the radio frequency exposure time (s) at different power levels during the radio frequency heating.

Equation number	Moisture content (% wet basis)	Power (kW)	Regression model	Degree of freedom	Correlation coefficient
3.5	9	3	$T = 0.00004t^2 + 0.073t + 297.116$	3	0.999
3.6	9	5	$T = 0.0002t^2 + 0.121t + 296.883$	3	0.971
3.7	9	7	$T = 0.0003t^2 + 0.156t + 296.989$	3	0.992

The developed regression models were used as input data in Equation 3.3 to estimate kinetic parameters of the thermal death of the adult *T. castaneum*.

3.5.2 Thermal mortality of the insects

Table 3.3 shows the measured survival rates of the adult *T. castaneum* in 9% MC samples during RF heating at 3 kW, 5 kW, and 7 kW from 297 K to 338 K. Highest end temperature of 338 K was chosen, as Yu et al. (2016) reported that 100% mortality of *T. castaneum* infesting the canola seeds at MCs of 5%, 7%, 9%, and 11% could be achieved without significant degradation of the seed quality at 333 K with proper design of RF heating applicators.

Table 3.3: Number of survived adult *T. castaneum* in 9% moisture content (wet basis) canola samples at different end temperatures (338 K, 333 K, 328 K, and 323 K) using radio frequency heating at different power levels (3 kW, 5 kW, and 7kW).

Power (kW)	Initial number of live insects	Time (s)	Number of alive insects
3	20	0±0	0.0±0.0
		304±4	14.6±0.6
		354±4	9.0±0.0
		402±4	7.0±0.0
		448±6	4.0±0.0
5		0±0	0.0±0.0
		172±6	15.0±0.0
		194±4	7.0±0.0
		220±4	4.0±0.0
		242±2	1.0±0.0
7		0±0	0.0±0.0
		122±8	10.6±0.6
		138±6	4.3±0.6
		156±4	2.0±0.0
		170±2	0.0±0.0

Note: Each mean represents the average of three replicates and represented as mean ± σ.

Usually, higher temperature leads to greater mortality percentage of insects. At any end temperatures of the seeds, the survival rate of the insect was inversely proportional to the power level. The insects mixed with the canola seeds were exposed to the evaporated steam from the moisture present in the seeds during RF heating. The survival rate of the insects in the seed samples at high power (7 kW) was lower than that at low power (3 kW) at the same end RF heating temperature. The dielectric loss factor of adult insects is higher than dielectric loss factor of the grains (Shrestha, and Baik 2013b; Yu et al. 2015), thus the insect body temperature during RF heating should be much higher than that of canola seeds as heating rate of an object is largely dependent on its dielectric loss factor during dielectric heating. However, fast heat transfer occurs by conduction from hotter insect body to surrounded colder canola seeds due to the large temperature gradient. This will reduce the effect of selective heating due to dielectric loss difference between insect body and canola seed. When the heating power increases, heating time to reach the same temperature decreases as shown in Table 3.3. Inferring, that the time for conductive heat loss from insect bodies to canola seeds is shorter, which proves that the efficiency of selective heating increases with the increase in RF power. In addition, proper mixing of adult *T. castaneum* and the canola samples was crucial as to distribute *T. castaneum* uniformly throughout the canola sample, to achieve unbiased results.

At 7 kW, 100% mortality of the insects was achieved at 338 K, over 95% mortalities of the insects were achieved at 338 K for the samples at 5 kW and over 80% mortalities of the insects were achieved at 338 K at 3 kW. The RF exposure times to achieve temperature from 297 K to 338 K were, 304 s to 448 s, 172 s to 242 s and 122 s to 170 s for the samples, treated at 3 kW, 5 kW, and 7 kW respectively. The thermal effect on the insect mortality was attributed to the thermal degradation of carbohydrates, proteins, DNA, RNA, and lipids of the insects (Hallman and Denlinger 1998).

3.5.3 Thermal death kinetics

To determine E_a for the thermal death kinetics of *T. castaneum* different values of k_0, E_a, and n were fitted in equation 3.3; the value of E_a, was chosen from 94 kJ/mol to 105 kJ/mol with an interval of 0.50 kJ/mol and the value, this range was considered as E_a, of adult *T. castaneum* was reported to 100.00 kJ/mol (Yu et al. 2017). For the value of n literature shows that the kinetics followed the 1st order reaction, for adult *T. castaneum* (Yu et al. 2017) also, Ben- Ialli et al. (2009) found that the 1st order model to be most desirable to ellaborate the thermal death kinetics of *E. kuehniella* (Zeller) eggs, comparing to the 0.5th order of reaction of the thermal death kinetics of the insect pests used by Wang et al. (2002a) and Johnson et al. (2003, 2004) and 0th order reaction of the thermal kinetics of the pest used by Yan et al. (2014). So, along with n=1 we also wanted to investigate the behavior of the kinetics at various values, slightly higher than n=1, therefore, in our case by increasing the value of n at an interval of 0.2 till the value of n is 2 and the behavior of the thermal kinetics were observed at each point. Along with the value of E_a and n, k_0 was chosen from 1.00×10^{13} s^{-1} to 9.50×10^{13} s^{-1} with an interval of 0.50×10^{13} s^{-1}. However, it should be noted that the kinetic parameters estimated were based on temperature histories of canola samples temperatures not on insects' temperatures.

Certain observations were recorded while trying to fit the simulated survival rates to the experimental survival rates: k_0 is proportional to E_a, n is also proportional to k_0 and E_a as shown in Table 3.4, therefore, to reduce and fit the value E_a within the range 94.00 kJ/mol to 105.00 kJ/mol the values of k_0 were reduced as the value of n increased. However, the performance of the kinetic model (Equation 3.3) in predicting the mortalities of the adult *T. castaneum* during the RF heating seems to be following 1st order or 1.2nd order, as the value of n increased the RMSE also increased, except in the case of 7 kW.

Table 3.4: Performance of the kinetic model (Equation 3.5) in predicting the mortalities of the adult *T. castaneum* during the radio frequency heating.

Power (kW)	Activation energy (kJ/mol)	Frequency factor (1/s)	Order of reaction (n)	Root mean square error
3	97.50	6.50×10^{13}	1.0	1.55
3	98.50	6.00×10^{13}	1.2	1.58
3	99.00	5.00×10^{13}	1.4	1.93
3	100.00	4.50×10^{13}	1.6	1.89
3	100.00	3.00×10^{13}	1.8	2.07
3	100.50	2.50×10^{13}	2.0	2.28
5	97.50	6.50×10^{13}	1.0	1.95
5	98.50	6.00×10^{13}	1.2	2.32
5	99.00	5.00×10^{13}	1.4	2.64
5	100.00	4.50×10^{13}	1.6	2.79
5	100.00	3.00×10^{13}	1.8	3.11

5	100.50	2.50×10^{13}	2.0	3.47
7	97.50	6.50×10^{13}	1.0	6.60
7	98.50	6.00×10^{13}	1.2	6.19
7	99.00	5.00×10^{13}	1.4	5.37
7	100.00	4.50×10^{13}	1.6	5.23
7	100.00	3.00×10^{13}	1.8	4.77
7	100.50	2.50×10^{13}	2.0	5.25

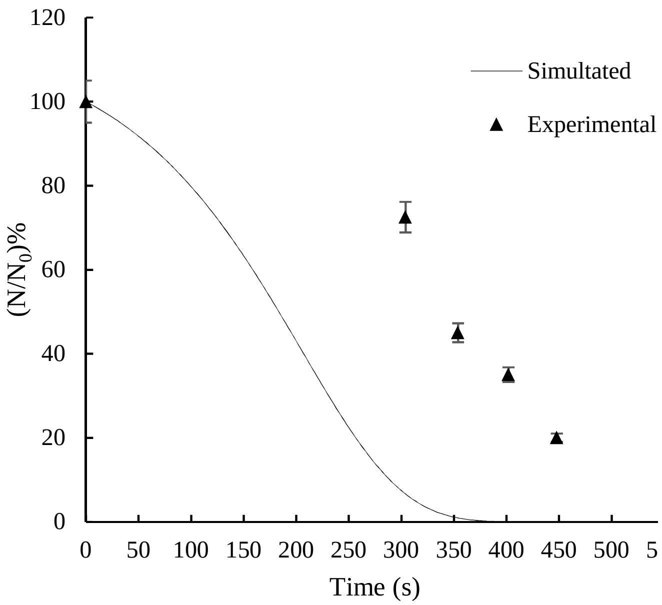
The best fitted kinetic model of thermal death of the adult *T. castaneum* in the canola seeds during RF heating was as follows.

$$\frac{d(N/N_0)}{dt} = -\,6.5 \times 10^{13}.\,exp\left(\frac{9.750 \times 10^{-4}}{RT}\right)\left(\frac{N}{N_0}\right)^{1} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.8)$$

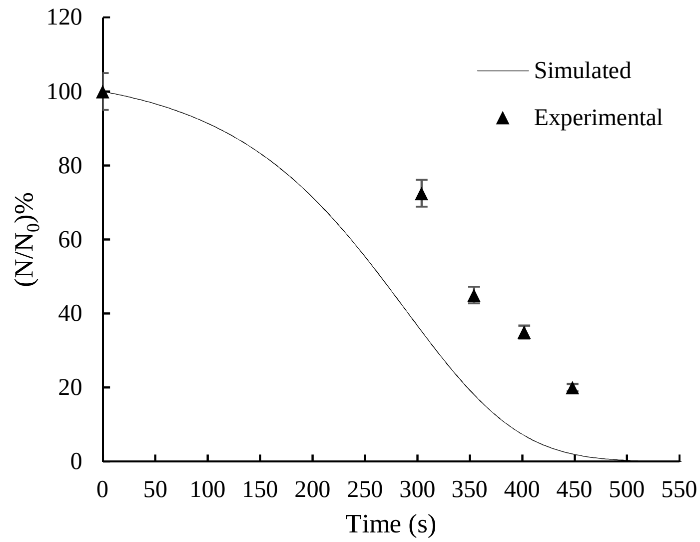
$$\frac{d(N/N_0)}{dt} = -\,6 \times 10^{13}.\,exp\left(\frac{9.850 \times 10^{-4}}{RT}\right)\left(\frac{N}{N_0}\right)^{1.2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.9)$$

The performance of the model in predicting the mortalities for both the small and the large volume samples is summarized in Table 3.4.The mortalities determined from the kinetic model agreed reasonably well with the experimental values resulting in RMSE of 7.95, 1.90, and 1.14 at 3 kW, 5 kW, and 7 kW, respectively. The kinetic parameters should be independent of MC and volume of samples if the effect of steam release is not reflected in the thermal death kinetics. Figure 3.6

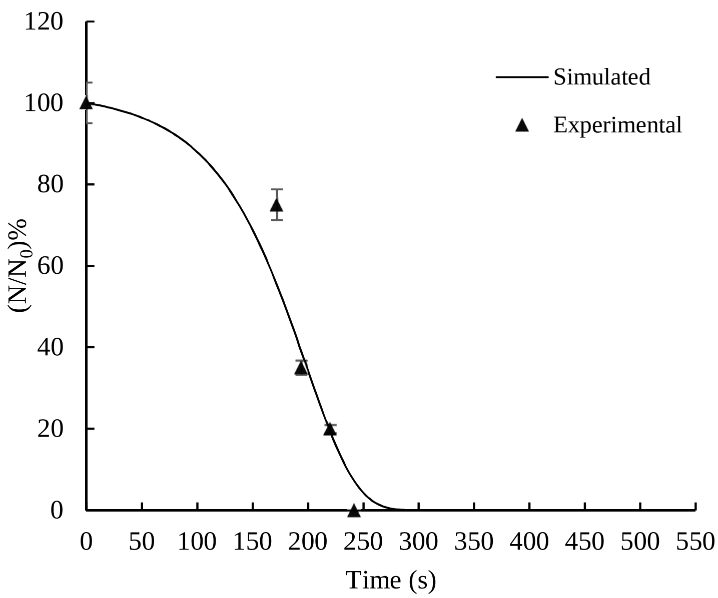
compares the survival rates of insects determined from the kinetic model with those from the experiments for canola samples at 3 kW, 5 kW, and 7 kW during the RF heating.



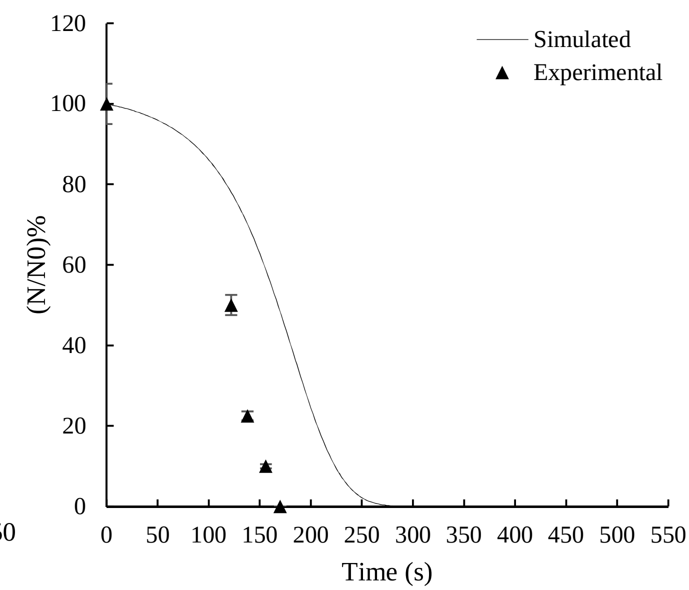
(a1)



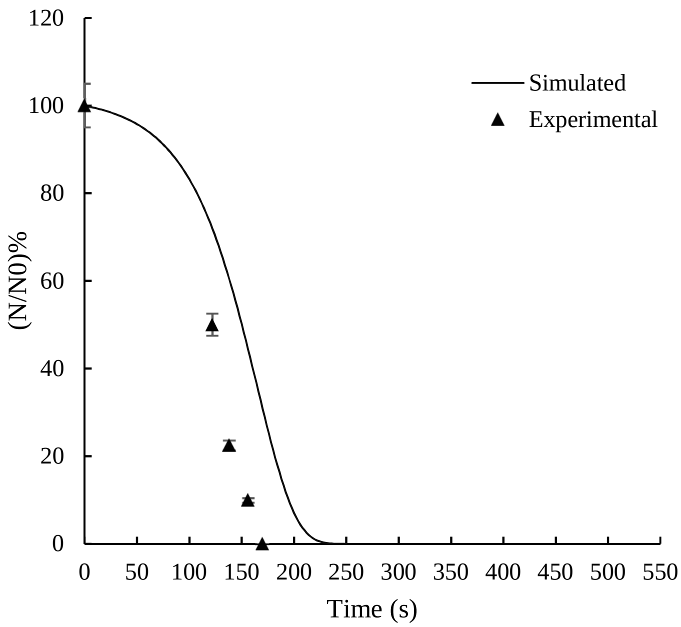
(a2)

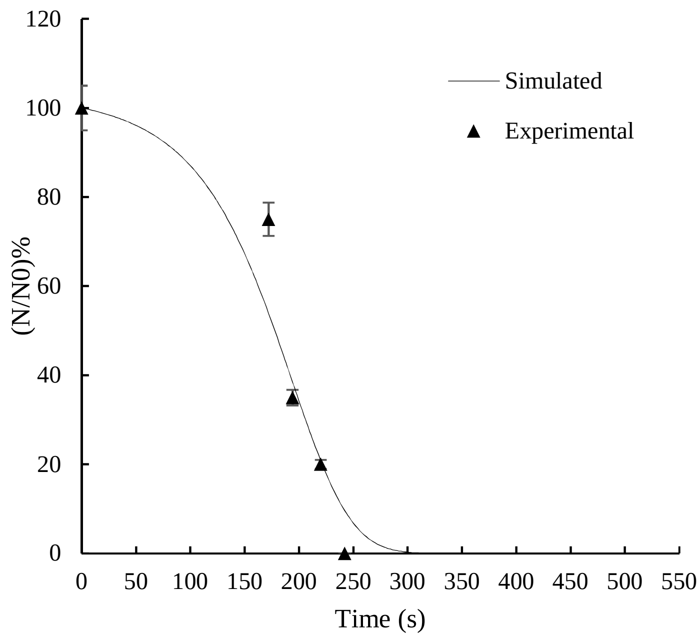


(b1)



(b2)





(c1) (c2)

Figure 3.6: Survival rates (alive insects%) of the adult *T. castaneum* infesting the canola samples of 9% moisture content (wet basis) during the radio frequency heating at 3 kW at *n*=1 (a1), 3 kW at *n*=1.2 (a2), 5 kW at *n*=1 (b1), 5 kW at *n*=1.2 (b2), 7 kW at *n*=1 (c1), 7 kW at *n*=1.2 (c2). Note: Error bars represent percentage errors generated from three readings recorded.

The kinetics followed the 1st order reaction, like Yu et al. (2017) for adult *T. castaneum*, also the kinetics seems to work well at 1.2nd order. Ben- Ialli et al. (2009) reported that the 1st order model was the most appropriate to describe the thermal death kinetics of eggs of *E. kuehniella* (Zeller) as well. When comparing to the 0.5th order of reaction of the thermal death kinetics of the insect pests used by Wang et al. (2002a) and Johnson et al. (2003, 2004) and 0th order reaction of the thermal kinetics of the pest used by Yan et al. (2014), the 1st order kinetic model was more suitable in our case similar to Yu et al. (2017). The determined E_a for the thermal death kinetics of *T. castaneum* was 97.50 kJ/mol at 1st order and 98.50 kJ/mol at 1.2nd order. However, since the determined E_a

for the thermal death kinetics of *T. castaneum* at 1st order is lower than 1.2nd order and the model also performed better at 1st order compared to 1.2nd order (refer Table 3.3), so, we considered 1st order to be the best fit.

However, it should be noted again that the kinetic parameters estimated were based on temperature histories of canola samples not on insect samples temperatures. The values are slightly lower than the adult *T. castaneum*, 100.00 kJ/mol (Yu et al. 2017), implying that our *T. castaneum* was more susceptible to RF energy than those used by Yu et al. (2017). This may be due to the type of applicator and the RF system used in both the cases considering both studies used grain temperature histories instead of insect body temperature histories for estimation of the kinetic parameters. Yu et al. (2017) used 1.5 kW, 27.12 MHz lab-scale RF system (Strayfield Fastran, Berkshire, England) with a conventional RF generator and a parallel electrodes applicator whereas, the RF system used in this research was 50-ohm technology-based pilot scale RF heating system that includes RFG (max. 15 kW and 27.12 MHz) with AMN, 50-ohm coaxial cable, and the custom-made RF applicator. The power generated was constantly maintained at a certain level throughout the operation in our research with the AMN and the 50-ohm coaxial cable, unlike fluctuating power levels in the conventional RF system which depends highly on the load applied. Also, the applicator used in this study was a tubular type with parallel plate electrodes with 30 cm between the plates. Likewise, the sample load was much greater than that used by Yu et al. (2017). Along with the difference in the types of RF systems used in both the cases the power levels (3 kW, 5 kW, and 7 kW) in our case were much higher compared to Yu et al. (2017). However, the difference was small, despite the difference in RF heating system, sample load size and power levels. Similarly, with the study of Ben-Ialli et al. (2009) on survival kinetics of *E. kuehniella* during 46°C -75°C heat treatment, the activation energy was 102.00 kJ/mol. In contrast with the other insect pests, the activation energy was higher such as the *A. transitella* (Walker) (510.00 kJ/mol to 520.00 kJ/mol) by Wang et al. (2002b); *P. interpunctella* (506.30 kJ/mol) by Johnson et al. (2003); and *C. pomonella* (472.00 kJ/mol) by Wang et al. (2002a); *D. armand* (430.00 kJ/mol) by Zhao et al. (2018); *A. ludens* (560.70 kJ/mol) by Hallman et al. (2005); and *S. oryzae* (505.00 kJ/mol) by Yan et al. (2014).

3.5.4 Lethal time

The developed kinetics model was reversibly used to estimate the lethal time (LT_{95}) and the LT_{99} at each power level. Table 3.5 shows the experimental LT required to kill 100% of the insect as well as the LT_{95} and the LT_{99} determined from the kinetics model.

Table 3.5: The radio frequency exposure times (s) to achieve 100% mortality and the lethal times determined from the numerically simulated data for the adult *T. castaneum* at the indicated radio frequency power levels.

Power (kW)	Numerically simulated RF exposure times (s)			
	Radio frequency exposure times for 100% mortality	**LT99**	**LT95**	**LT90**
3	448	354	312	288
5	314	268	248	236
7	258	220	204	194

The thermal death kinetics model was used to predict the RF exposure LT for the insect pests. Table 3.5 shows the numerically simulated heating time for the insect pests to achieve 100%, LT_{99}, LT_{95}, and LT_{90} at three RF power levels (3 kW, 5 kW, and 7 kW) of *T. castaneum* during RF heating. The predicted lethal time for 100% mortality rate at the entire power level ranged from 258 s to 448 s. Whereas, for LT_{99}, 220 s to 354; LT_{95}, 204 s to 312 s; and for LT_{90}, 190 s to 288 s.

Shorter RF exposure time was achieved at a higher RF power level at all mortality rates of the insect pests. This was attributed to the slow heating rate in the lower RF power level. LT_{95} and LT_{99} at 5 kW and 7 kW of mortalities of *T. castaneum* were much lower than the ones observed by Yu et al., (2017) at 9% MC canola samples. This means disinfestation of the insect by RF could be done more effectively at higher RF power levels due to shorter RF heating time and steam release effect to achieve the specific mortalities compared to seeds at lower MC.

3.6 Conclusions

The survival rate of the adult *T. castaneum* infesting the canola seeds at 9% MC decreased with an increase in temperature (297 K to 338 K) and increase in RF power levels (3 kW to 7 kW) during RF heating. The kinetic parameters of the thermal death of the adult *T. castaneum* were estimated using an inverse simulation. The kinetics followed first-order reaction with the activation energy of 97.50 kJ/mol and it produced the insect mortalities that were comparable to the experiments. The determined LTs from the experiments and the kinetic model were in good agreement. The thermal death kinetic model developed in this research would be useful in designing post-harvest RF thermal processes to control *T. castaneum* and similar insects in stored canola seeds and other commodities.

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3.8 References

ASAE. 2002. ASAE S352.2, moisture measurements-unground grains and seeds. In ASAE standards. St. Joseph, MI, USA.

Ben-Ialli, A., J. M. Méot, P. Bohuon and Collignan, 2009. Survival kinetics of Ephestia kuehniella eggs during 46–75 C heat treatment. *Journal of Stored Products Research*, 45 (3): 206-211.

Birla, S. L., S. Wang, J. Tang and G. Tiwari. 2008. Characterization of radio frequency heating of fresh fruits influenced by dielectric properties. *Journal of Food Engineering*, 89(4):390-398.

Brusewitz, G. H. 1975. Density of rewetted high moisture grains. *Transactions of the ASAE*, 18 (5):935-938.

Canola Council of Canada. 2019. https://www.canolacouncil.org/markets-stats/industry-overview/ . (May 18, 2019).

Canola Watch. 2015. http://www.canolawatch.org/2011/05/09/estimating-flea-beetle-damage-in-canola/ . (May 18, 2019).

Coaxial Power System Ltd. 2018. https://www.coaxialpower.com/rf-matching-networks-tuners.html (May 18, 2019)

Gao, M., J. Tang, Y. Wang, J. Powers and S. Wang. 2010. Almond quality as influenced by radio frequency heat treatments for disinfestation. *Postharvest Biology and Technology*, 58:225–231.

Griffin, J. P. 1988. Montreal Protocol on Substances That Deplete the Ozone Layer. In Int'l L. Volume 22:1261.

Hallman, G. J. and D. L. Denlinger. 1998. Temperature sensitivity in insects and application in integrated pest management, 7-53. NY, USA: Westview Press, Inc.

Hallman, G. J., and S. Wang and J. Tang. 2005. Reaction orders for thermal mortality of third instars of Mexican fruit fly (Diptera: Tephritidae). *Journal of Economy Entomology*, 98:1905-1910.

Heather, N. W. and G. J. Hallman. 2008. Pest management and phytosanitary trade barriers. Oxfordshire, UK: CABE.

Jiao, S., J. A. Johnson, J. Tang, G. Tiwari and S. Wang. 2011. Dielectric properties of cowpea weevil, black-eyed peas and mung beans with respect to the development of radio frequency heat treatments. *Biosystems Engineering*, 108 (3):280-291.

Johnson, J. A., K. A. Valero, S. Wang and J. Tang. 2004. Thermal death kinetics of red flour beetle (Coleoptera: Tenebrionidae). *Journal of Economic Entomology,* 97(6):1868-1873.

Johnson, J. A., S. Wang and J. Tang. 2003. Thermal death kinetics of fifth instar Plodia interpunctella (Lepidoptera: Pyralidae). *Journal of Economic Entomology*, 96(2):519-524.

Lagunas-Solar, M. C., Z. Pan, N. X. Zeng, T. D. Truong, E. Khir and K. S. P. Amaratunga. 2007. Application of radio frequency power for non-chemical disinfestations of rough rice with full retention of quality attributes. *Applied Engineering in Agriculture,* 23(5):647–654.

Manickavasagan, A, D. S. Jayas and N. D. G. White. 2006. Non-uniformity of surface Temperatures of grain after microwave treatment in an industrial microwave dryer. *Drying Technology*, 24(12):1559-1567.

Shivhare, U. S., G. S. V. Raghavan and R. G. Bosisio. 1992. Microwave drying of corn II. Constant power, continuous operation. *Transactions of the ASAE*, 35(3):951–957.

Shrestha, B. L., D. Yu and O. D. Baik. 2013a. Elimination of *Cruptolestes Ferrungineus* S. in Wheat by Radio Frequency Dielectric Heating at Different Moisture Contents. *Progress in Electromagnetics Research*, 139:517-538.

Shrestha, B. L., and O. D. Baik. 2013b. Radio frequency selective heating of stored-grain insects at 27.12 MHz: A feasibility study. *Biosystems Engineering* 114(3):195-204.

Sinha, R. N. and F. L. Watters. 1985. Insect pests of flour mills, grain elevators, and feed mills and their control (No. 1776). Ottawa, Canada: Agriculture Canada

Soysal, Y. 2004. Microwave drying characteristics of parsley. *Biosystems Engineering*, 89(2): 167–173.

Tang, J., J. N. Ikediala, S. Wang, J. D. Hansen and R. P. Cavalieri. 2000. High-temperature-short-time thermal quarantine methods. *Postharvest Biology and Technology*, 21(1):129-145.

USDA Foreign Agricultural Service. 2015. Production, Supply and Distribution Online Database, query for Commodity: "Oilseed, Rapeseed"; Data Type: "Production"; Country: "All countries"; Year: "2018", (May 18, 2019). https://www.fas.usda.gov/commodities/other-oilseeds

Wang, S., J. Tang, and J. D. Hansen. 2007. Experimental and simulation methods of insect thermal death kinetics. In: Tang, J., Mitcham, E., Wang, S., Luire, S., (Eds), Heat Treatments for Postharvest Pest Control: Theory and Practice (pp. 105-128). Oxfordshire, UK: CABI.

Wang, S. and J. Tang. 2004. Radio frequency heating: a potential method for post-harvest pest control in nuts and dry products. *Journal of Zhejiang University Science* 5(10):1169-1174.

Wang, S., J. N. Ikediala, J. Tang and J. D. Hansen. 2002a. Thermal death kinetics and heating rate effects for fifth instar *Cydia pomonella* (L.) (Lepidoptera: Tortricidae). *Journal of Stored Products Research*, 38(5):441-453.

Wang, S., J. Tang, J. A. Johnson and J. D. Hansen. 2002b. Thermal-death kinetics of fifth instar *Amyelois transitella* (Walker) (Lepidoptera: Pyralidae). *Journal of Stored Products Research*, 38 (5):427-440.

Yan, R., Z. Huang, H. Zhu, J. A. Johnson and S. Wang. 2014. Thermal death kinetics of adult *Sitophilus oryzae* and effects of heating rate on thermotolerance. *Journal of Stored Products Research*, 59:231-236.

Yu, D. U., B. L. Shrestha and O. D. Baik. 2015. Radio Frequency Dielectric Properties of Bulk Canola Seeds under Different Temperatures, Moisture Contents, and Frequencies for Feasibility of Radio Frequency Disinfestation. *International Journal of Food Properties*, 18(12):2746-2763.

Yu, D., B. Shrestha and O. D. Baik. 2016. Radio frequency (RF) control of red flour beetle (*Tribolium castaneum*) in stored rapeseeds (*Brassica napus* L.). *Biosystems Engineering*, 151: 248-260.

Yu, D., B. Shrestha and O. D. Baik. 2017. Thermal death kinetics of adult red flour beetle *Tribolium castaneum* (Herbst) in canola seeds during radio frequency heating. *International Journal of Food Properties*, 20:3064-3075.

Zhao, L., H. Ramaswamy and S. Wang. 2018. Thermal-death kinetics of the bark beetle (Dendroctonus armandi; Coleoptera: Scolytidae). *Scandinavian Journal of Forest Research*, 33(8):735-740.

CHAPTER 4

General discussions

This chapter presents the integration of all the important results and observations from all the three chapters. Also, this chapter highlights the important contributions of this research for development of knowledge on implementation of RF heating system in disinfestation of insects in stored grains. In addition, important suggestions and recommendations to improve the efficiency of a 50-ohm RF system with a parallel plate through field type applicator are also discussed.

4.1 Temperature distribution of bulk canola seeds (9% MC) in the 50-ohm RF heating system with a parallel plate through field type applicator

The 50-ohm RF heating system with a parallel plate through field type applicator suffered non-uniformity in heating distribution when heating the canola seeds at 9% MC. The spot with the highest heating rate was found adjacent to the hot electrode, whereas, the spot with the lowest heating rate was found adjacent to the cold electrode. Uniform distribution of EM field in the RF heating of the samples is crucial for uniform temperature distribution throughout the sample (Huang et al. 2016; Wang et al. 2007). Also, the thermal properties, physical properties, electrical properties, size, shape, and position of the sample in the RF applicator affect the temperature distribution in the RF heating system (Yu et al. 2016). The electric field in a parallel plate through type applicator generally has a uniform field strength distribution, as stated by Huang et al. (2018). Also, the electric field strength distribution is affected by the presence of the sample, the sample size, and position of the sample in between the electrodes (Huang et al. 2018; Llave et al. 2015).

Likewise, literature shows that variation in temperature distribution during RF heating of agricultural commodities is a major challenge in implementing RF heating systems (Yu et al. 2016; Jiao et al. 2015; Alfaifi et al. 2014; Gao et al. 2010). Since, the applicator structure was made with polypropylene composite component, Dabbak et al. (2018) showed that at higher frequencies higher than 3 kHz polymer composites exhibits ionic polarization, this might have interfered with the electric field causing disturbance in the heating mechanism along with the air present in between the particles of the bulk canola. Also, since the canola seeds were packed in polypropylene bags the evaporated steam could not travel throughout the sample load, thus causing raise in temperature in local spots rather than the whole system.

4.2 Disinfestation of adult red flour beetles infesting canola seeds using 50-ohm radio frequency (RF) heating system

The mortality of adult red flour beetles infesting the canola seeds at 9% MC was directly proportional to the temperature (297 K to 338 K), and the RF power levels (3 kW to 7 kW) during RF treatment process. As the dielectric loss factor of adult insects is higher than that of the canola (Shrestha and Baik, 2013; Yu et al. 2015), the insect body temperature raised at much higher rate than the canola seeds during the RF heating, proving the effectiveness of selective heating. However, fast heat transfer happened by conduction, transferring heat from the hotter insect bodies to the colder canola seeds due to the large difference in temperature between them, thus reducing the effect of selective heating. However, at higher power since the heating time to reach the same lethal temperature decreased in relation to the lower RF power, the time for conductive heat loss from insect bodies to canola seeds was shorter, which increased the efficiency of selective heating at higher RF power.

The thermal kinetics adult red flour beetles best fitted the 1st order reaction with an activation energy of 97.50 kJ /mol, the determined LTs from the experiments and the kinetic model were in good agreement as shown in literature (Yu et al. 2017; Ben-Ialli et al. 2009; Wang et al. 2002b; Johnson et al. 2003; Wang et al. 2002a; Zhao et al. 2018; Hallman et al. 2005; Yan et al. 2014).

4.3 Post-treatment quality of canola seeds after 50-ohm RF heating treatment at different power levels.

Different quality parameters of canola seeds including MC, germination rate, colour and oil quality of canola seeds before and after RF heating at various end temperatures (50°C, 55°C, 60°C, and 65°C) and various power levels (3 kW, 5 kW, and 7 kW) were considered. The MC decreased with the increase of temperature; however, with the increase in power, the difference in MC remains relatively similar. Colour of the canola seeds changed after the RF treatment. However, there no major changes in germination rates of the canola seeds after RF treatment and the quality of the oil after the RF heating operation.

4.4 Contribution to academic knowledge development

The idea of this research relied on principles and heating characteristics of EM waves, which exhibits a dielectric heating pattern. So, one of the crucial parameters involved the dielectric properties of the canola seeds and red flour beetles infesting the stored canola seeds. Literature shows that dielectric loss factor of the two subjects (canola seeds, and red flour beetles) vary drastically especially when the stored seeds are at lower MC, where, the canola seeds have lower dielectric loss factor compared to the red flour beetles (Shrestha and Baik 2013; Yu et al. 2015). Due to the difference in the dielectric loss factor the insect body temperature raised at a much higher rate than the canola seeds during the RF heating, proving the effectiveness of selective heating. Also, as the power increased, the conductive heat transfer between the insect bodies and the canola seeds decrease as the heating time to reach the same lethal temperature decreased in relation to the lower RF power, which increased the efficiency of selective heating at higher RF power. Thus, the disinfestation of red flour beetle from stored canola was a successful process using the 50-ohm RF heating system with a parallel plate through field type applicator. This observation is crucial, as it opens up the opportunity to learn the heating characteristics of different biological commodities with different dielectric properties at different power levels, to enhance the use of 50-ohm RF heating system with a parallel plate through field type applicator. As, 50-ohm RF system can maintain constant frequency and power load through a matching network, and the electric field in a parallel plate through type applicator generally has a uniform field strength distribution, as stated by Huang et al. (2018). The opportunities for use of a 50-ohm RF heating system with a parallel plate through field type applicator in the processing of biological commodities may include all the heat treatments involved in the process. Although the process of disinfestation was a success, the use of RF heating does come with some major challenge which is generation of spots with different heating rates as seen in this study and several other researchers have also shown similar results (Yu et al. 2016; Jiao et al. 2015; Alfaifi et al. 2014; Gao et al., 2010). The uniformity in heating rates in different spots of the sample relies on the distribution of EM field in the RF heating of the samples (Huang et al. 2016; Wang et al. 2007). The uniformity in EM field distribution that depends on thermal properties, physical properties, electrical properties, size, shape, and the position of the sample in the RF applicator affects the temperature distribution in the RF heating system (Yu et al. 2016). Thus, a thorough understanding of all the parameters involved in RF heating operation is very important and understanding of all the parameters is a huge challenge and opportunity to improve any RF heating operation. Some recommendations and suggestions to improve the efficiency of the 50-ohm RF heating system with a parallel plate through field type applicator are given below in the following section.

4.5 Recommendations for future studies

Along with this study, several other researchers have also shown that the electric field strength in parallel plate electrodes is dependent on the geometry, volume, size, physicochemical properties, electrical properties, and orientation of the sample (Huang et al. 2018; Huang et al. 2016; Llave et al. 2015; Wang et al. 2007; Yu et al. 2016). Thus, it is crucial to study the characteristic effects of all the parameters involved in RF heating to better design an optimum RF heating system. The 50-ohm RF heating system used in this research consisted of a parallel plate through field type applicator with a tubular channel, horizontally oriented, and constructed using polypropylene composite; 30 cm (diameter), and 70 cm (length) and gap of 36 cm in between the two electrodes. The electrodes were connected to the matching network at the inner zone of the applicator. The construction was done with the assumption of uniform distribution electric field in between the parallel plate electrodes, and the tubular channel was constructed with polypropylene composite assuming that electric fields can be transferred to the sample without disturbance as polypropylene is considered dielectric transparent material. However, the construction and orientation of the applicator suffered non-unifromity in the heating rates at different spots throughout the applicator considering the results and observations from Chapter 2.

So, studying the heating characteristics of agricultural commodities by changing the dimensions and orientation of the applicator can help explore new heights in developing a better and efficient RF heating system for agricultural commodities. With this thought, the Department of Chemical, and Biological Engineering, University of Saskatchewan in association with Prairie Agricultural Machinery Institute (PAMI), Humbolt, and Engineering Shop, University of Saskatchewan have developed a new applicator. The newer version of the applicator is vertically oriented to use the gravitational force to the advantage, also the dimensions have been updated to a smaller one by reducing the gap between the electrode to 10 cm and the polypropylene composite has been replaced by Teflon which is expected to better at being an RF transparent material (Figure 4.1), also an inline process can be devolved for a continues process by introducing auger system (Figure 4.2). Preliminary results using different agricultural commodities including chickpeas, and red lentils have shown promising results. Thus, the 50-ohm RF heating system has immense potential in any heat treatment processed involved in agricultural product industries. In addition, a coaxial structure of electrodes can be also considered for future studies.

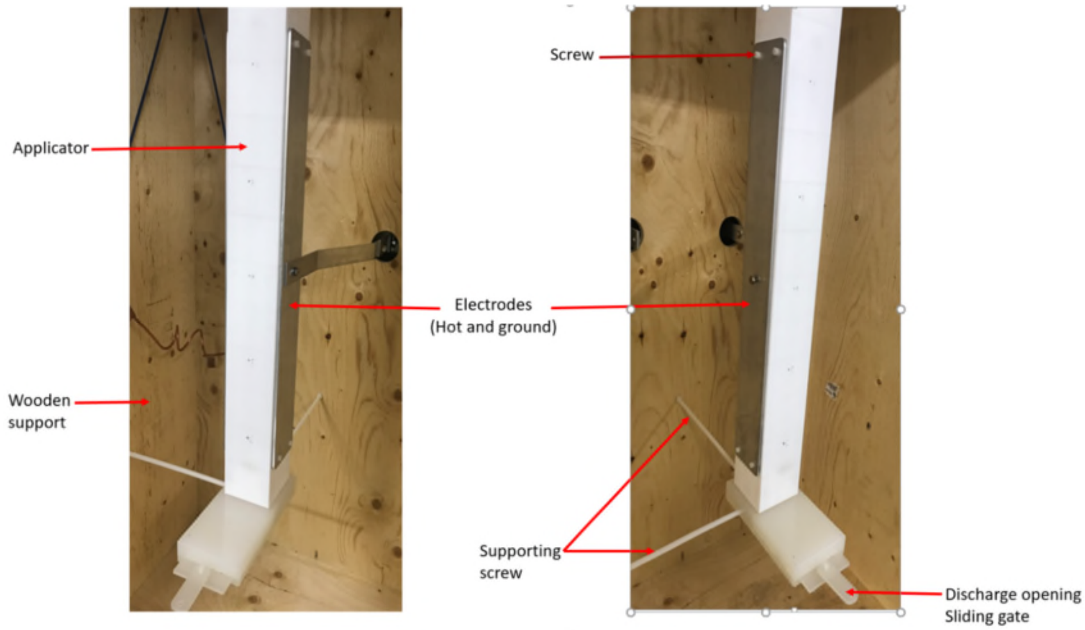

Figure 4.1: Vertically oriented parallel plate through field type applicator with an electrode gap of 10 cm and teflon composite tubular channel.

Figure 4.1: Vertically oriented parallel plate through field type applicator and teflon composite augur system.

4.6 References

Alfaifi, B., J. Tang, Y. Jiao, S. Wang, B. Rasco, S. Jiao and S. Sablani. 2014. Radio frequency disinfestation treatments for dried fruit: model development and validation. *Journal of. Food Engineering*, 120:268–276.

Ben-Ialli, A., J. M. Méot, P. Bohuon and Collignan. 2009. Survival kinetics of *Ephestia kuehniella* eggs during 46–75 C heat treatment. *Journal of Stored Products Research,* 45 (3):206-211.

Dabbak, S. Z. A., H. A. Illias, B. C. Ang, N. A. A. Latiff and M. Z. H. Makmud. 2018. Electrical properties of polyethylene/polypropylene compounds of high-voltage insulation. *Energies,* 11(1448):1-13.

Gao, M., J. Tang, Y. Wang, J. Powers and S. Wang. 2010. Almond quality as influenced by radio frequency heat treatments for disinfestation. *Postharvest Biology and Technology*, 58(3):225-231.

Hallman, G. J., S. Wang and J. Tang. 2005. Reaction orders for thermal mortality of third instars of Mexican fruit fly (Diptera: Tephritidae). *Journal of Economy Entomology*, 98:1905-1910.

Huang, Z., F. Marra and S. Wang. 2016. A novel strategy for improving radio frequency heating uniformity of dry food products using computational modeling. *Innovative Food Science and Emerging Technologies,* 34:100–111.

Huang, Z., F. Marra, J. Subbiah and S. Wang. 2018. Computer simulation for improving radio frequency (RF) heating uniformity of food products: A review. *Critical Reviews in Food Science and Nutrition,* 58(6):1033-1057.

Jiao, S., Y. Deng, Y. Zhong, D. Wang and Y. Zhao. 2015a. Investigation of radio frequency heating uniformity of wheat kernels by using the developed computer simulation model. *Food Research International*, 71:41–49.

Johnson, J. A., S. Wang and J. Tang. 2003. Thermal death kinetics of fifth instar Plodia interpunctella (Lepidoptera: Pyralidae). *Journal of Economic Entomology*, 96 (2):519-524.

Llave, Y., S. Liu, M. Fukuoka and N. Sakai. 2015. Computer simulation of radiofrequency defrosting of frozen foods. *Journal of Food Engineering*, 152:32–42.

Shrestha, B. L. and O. D. Baik. 2013. Radio frequency selective heating of stored-grain insects at 27.12 MHz: A feasibility study. *Biosystems Engineering* 114(3):195-204.

Wang, S, M. Monzon, J. Johnson, E. Mitcham and J. Tang. 2007. Industrial-scale radio frequency treatments for insect control in walnuts: I: Heating uniformity and energy efficiency. *Postharvest Biology and Technology*, 45(2):240-246.

Wang, S., J. N. Ikediala, J. Tang and J. D. Hansen. 2002a. Thermal death kinetics and heating rate effects for fifth instar *Cydia pomonella* (L.) (Lepidoptera: Tortricidae). *Journal of Stored Products Research*, 38 (5):441-453.

Wang, S., J. Tang, J. A. Johnson and J. D. Hansen. 2002b. Thermal-death kinetics of fifth instar *Amyelois transitella* (Walker) (Lepidoptera: Pyralidae). *Journal of Stored Products Research*, 38 (5):427-440.

Yan, R., Z. Huang, H. Zhu, J. A. Johnson and S. Wang. 2014. Thermal death kinetics of adult *Sitophilus oryzae* and effects of heating rate on thermotolerance. *Journal of Stored Products Research*, 59:231-236.

Yu, D., B. L. Shrestha and O. D. Baik. 2016. Temperature distribution in a packed bed of canola seeds with various moisture contents and bulk volumes during radio frequency (RF) heating. *Biosystems Engineering*, 148:55-67.

Yu, D. U., B. L. Shrestha and O. D. Baik. 2015. Radio Frequency Dielectric Properties of Bulk Canola Seeds under Different Temperatures, Moisture Contents, and Frequencies for Feasibility of Radio Frequency Disinfestation. *International Journal of Food Properties*, 18(12):2746-2763.

Yu, D., B. Shrestha and O. D. Baik. 2017. Thermal death kinetics of adult red flour beetle *Tribolium castaneum* (Herbst) in canola seeds during radio frequency heating. *International Journal of Food Properties*, 20:3064-3075.

Zhao, L., H. Ramaswamy and S. Wang. 2018. Thermal-death kinetics of the bark beetle (Dendroctonus armandi; Coleoptera: Scolytidae). *Scandinavian Journal of Forest Research*, 33(8):735-740.