RADIO FREQUENCY HEATING FOR DEHYDRATION AND PEST CONTROL OF IN-SHELL PEANUTS

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RADIO FREQUENCY HEATING FOR DEHYDRATION AND PEST CONTROL OF IN-SHELL PEANUTS

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THESIS ABSTRACT

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For many decades conventional wagon drying (curing) systems or batch/continuous flow drying systems have been used for peanut dehydration. Both are time and energy consuming. Radio Frequency (RF) dielectric heating has been applied to many types of food processing including tree nut. In this study, we would like to apply RF energy to dehydration and pest control of in-shell peanuts. RF is a fast and effective alternative drying method because heat is generated by the interaction between RF energy and moisture inside in-shell peanuts. In RF heating applications, the drying energy is evolved from inside the products. This will not only save time and energy, but will also eliminate or reduce thermal abuse to the products compared to the conventional processes.

Despite the effectiveness of this method, it also presents some difficulties in its application. Primarily, RF heating or dehydration of peanuts process is non-uniform.

Non-uniformity of RF heating of peanuts is due to many circumstances that have been discussed and taken into consideration in the RF treatment protocol. In this treatment protocol we overcome non-uniformity using multiple numbers of RF heating cycles with intermittent stirring and cooling. A set of 6 runs (each run consisting of a RF heating cycle followed by intermittent stirring and cooling cycle) were designed to dry peanuts at three different targeting temperatures of 40, 50 and 60 °C. The quality of peanuts after RF treatments at 40 or 50 °C are acceptable while the quality at 60 °C is not acceptable due to the percentage of broken and shelled peanuts. For the three targeting temperatures, the total RF heating time was in the range of 10 to 20 minutes. We found that the relation between peanut kernels' temperature and the time of RF heating could be fitted in a straight line.

In the second part of this work we studied the mortality of Red Flour Beetles (RFB), which are the most heat resistant insects that live in peanuts. We used a custom built heating block system manufactured by the Washington State University (WSU). We found different results from those in the literature on RFB. In our results RFB showed resistance to similar time-temperature combinations used before in others' research. These results indicate that RFB in the southeastern area of the United States are more thermal resistant than those in the west coast. Further research with increased heating temperature, increased heating time or both are needed. In addition, it is necessary to review the nature of heat transfer differences between RF heating and conduction heating in the WSU heating block system.

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VITA

Hatem Harraz, son of Mohamed Azmy Harraz and Hekmat Attia, was born in March 27th, 1970 in Cairo, Egypt. In 1992 he graduated with a Bachelor degree in chemical engineering from Faculty of Engineering, Cairo University, Cairo, Egypt. He finished his first Master's degree in Chemical Engineering from Chemical and Biochemical Engineering Department, Salford University, Salford, England in May 1995, and then he worked in the Oil & Gas Industry for about eight years in multinational companies as a process and senior process engineer. In August, 2002 he joined Auburn University and worked in Chemical Engineering Department as a Graduate Research Assistant in the area of biomass-to-ethanol. He framed his work with his advisor in a US Patent for producing an innovative form of cellulose. In August 2005 he joined the Biosystems Engineering Department at Auburn University to pursue his second master's degree with research on Radio Frequency applications for dehydration and pest control of peanuts under supervision of Dr. Yifen Wang. He started his work with Harris Group Inc. as a Senior Process Engineer in Seattle, Washington in June 2006.

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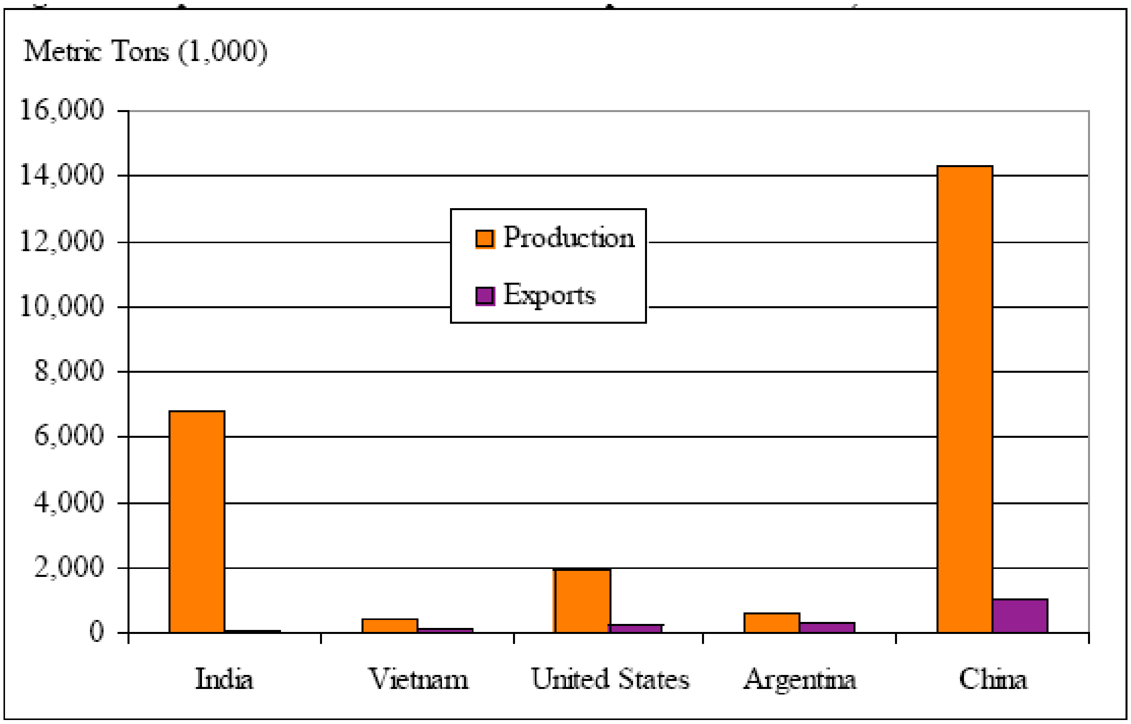
INTRODUCTION

The United States is the largest producer of nuts in the world, representing approximately two-thirds of the world nut trade. Figure 1. shows the top five world producers and exporters of peanuts in 2004. California is the leading state in nut production in the US with the major crops of almonds, walnuts and pecans. Georgia peanut production accounted for 40% of the U.S. crop in 2002. Alabama comes the second in planting and harvesting peanuts after Georgia, which commonly ranks first in the United States in peanut acreage planted and acreage harvested. Planted acreage from 2000-2002 ranged from 494,000 (2000) to 515,000 (2001) acres. Acreage harvested ranged from 492,000 (2000) to 515,000 (2001) acres. More information concerning yield/acreage/price/etc. is available at these web sites, (USDA, National Agricultural Statistics Service, 2007). Table 1 represents the acres planted and harvested in the last three years in Alabama as well as the production pounds per one harvested acre and the total peanuts produced.



Source: USDA Economic Research Service, Supply, Production, and Demand Data

Figure 1. Top Five World Producers and Exporters of Peanuts, 2004

Table 1. Planted and Harvested Acres of Peanuts in Alabama and Production in 2005-2006. (USDA, National Agricultural Statistics Service, last update February 20, 2007)

	2004	*2005*	*2006*
Planted Acres	200,000	225,000	165,000
Harvested Acres	199,000	223,000	163,000
Yield per Acre, lbs	2,800	2,750	2,500
Production, lbs	557,200,000	613,250,000	407,500,000

In 2005 the total planted acres of peanuts were 1,657,000. Of these planted acres, 98.3% have been harvested with an average 2,989 lb/acres. The average selling price was $0.174/lb with total revenue of $845,873,000. In 2006 the total planted acres were 1,243,000 and 1,209,000 harvested (97.3%) with an average 2,874 lb/acres harvested. This means the total produced peanuts in the United States last year was 3,474,450 thousands pounds.

Every 100 grams of fresh or roasted peanuts contain 24 grams protein, 50 grams fat, and 9 grams carbohydrates. The energy to be obtained from 100 grams of peanuts is 570 Kcal.

Americans consume large quantities of peanuts. The peanut is not actually a nut at all, but rather a legume. It is not clearly associated with some of the heart protective benefits of true nuts, but is considered to be a relatively inexpensive form of high quality protein.

In the past ten years, peanut harvest capacity in the US has increased dramatically with no appreciable change in commercial drying (curing) methods or equipment (Sanders, *et. al.*, 2001). The conventional wagon drying method is still the predominant method of drying. This method is based on loading peanuts during harvest into perforated wagons for transport and curing (or drying). Drying occurs when hot air is forced through the perforated flax of the wagon. The disadvantages of this method are high energy consumption, long drying times (typically more than one day) and problems relating to non-uniformity of airflow and variable temperature distribution over the peanut load.

In the continuous airflow dryer system, the problems of non-uniformity and variable distribution in temperature are improved but the process still consumes a tremendous amount of heat and time.

An example of the conventional wagon drying method can be found in the southeastern U.S. Peanuts are usually allowed to partially cure in the windrow for three to seven days; they are then harvested, and placed in drying wagons with a perforated plenum floor. Each four to six loads are mechanically cured by forcing heated air up through a 1.5 m deep bed of peanuts until the moisture content of the peanut kernel is less than 0.11 kg kg−1.

Young et al. (1982) developed optimum plenum conditions for curing peanuts. Temperatures in excess of 35 °C were shown to increase the risk of the development of off-flavors (Whitaker and Dickens, 1964) and removing moisture too rapidly increased the incidence of split kernels and loose skins (Beasley and Dickens, 1963; Troeger, 1989). The current recommendation consists of heating air 8–11 °C above ambient so as not to exceed 35 °C (Samples, 1984; Cundiff et al., 1991).

There are two additional problems with the use of hot air in peanut treatment: the low thermal conductivity of the peanut shell and the voids within the shell. These interfere with the transfer of thermal energy from the hot air outside to the inside of the shell where the kernel exists. Peanut kernels are meant to be dried, and by using the conventional method most of the energy will be lost before it transfers from outside the shell to the kernel.

Steele (1982) developed and implemented a microprocessor temperature controlled system for curing peanuts in Virginia. This process increased peanut drying time 10% while reducing consumption of liquefied petroleum gas (LPG) and electricity by 49% and 33%, respectively, compared to conventional dryer controls. However, the complexity of the hardware and software prevented commercial adaptation of this technology.

Baker et al. (1993) used regression analysis to fit three separate line segments to the upper limit of the preferred curing zone specified by Young et al. (1982). Using the drying rate control (DRC) in Virginia, reduced percent skin slippage approximately 30% compared with similar curing times and fuel costs.

Butts (1996) manually controlled plenum temperatures, to maintain a plenum relative humidity between 40 and 60%. Drying time increased 56% and energy consumption decreased 30% compared to conventional constant set point controls. However, labor availability for commercial peanut drying facilities prohibits manual manipulation of individual thermostat settings.

Butts, C. L., et al. (1998) reduced the DRC used by Baker et al. (1993) to a single equation and used a microprocessor to control a commercial peanut dryer. Under typical weather conditions experienced in South Georgia during the peanut harvest, the plenum temperature remained fairly constant (± 2 °C) throughout the 24-h drying cycle. The purpose of this research was to determine the optimum peanut curing temperature control algorithm in order to minimize drying time and minimize detrimental effects on resulting peanut quality.

There is considerable interest in the use of other alternatives to replace the conventional drying/curing system. One of these alternatives is the radio frequency (RF) energy as we will research and discuss that later in details. The RF method can be used for both drying and disinfestations of fruits and nuts.

The principle upon which RF treatment is based, is that the energy of RF interacts directly with a dielectric material, such as a nut, to generate heat by converting electromagnetic energy into thermal energy, thereby tremendously reducing the heating time (Tang et al., 2000).

LITERATURE SURVEY

DIFFERENT TREATMENT PROCESSES USED IN INFESTATION OF INSECT PESTS IN NUTS

Presently, there are five well known potential quarantine treatment methods used to combat infestation of insect pests such as red flour beetle *(Tribolium castaneum)*, codling moth *(Cydia pomonella)*, navel orangeworm *(Amyelois transitella)*, and Indian meal moth *(Plodia interpunctella)*. These quarantine methods, used for, both the domestic and international nut markets, are:

1- Chemical fumigation,
2- Ionizing radiation, controlled atmosphere,
3- Conventional hot air or water heating,
4- Cold treatment,
5- Dielectric heating using radio frequency (RF) and microwave (MW) energy.

Infestation with insect pests is generally a major problem in producing, storing and marketing nuts. Postharvest control of insects in nuts is essential for quarantine regulations in many countries. Larvae of codling moths are targeted by quarantine regulations in Japan and South Korea, and navel orangeworm is of phytosanitary concern for Australia (S. Wang and J. Tang, 2001).

The traditional treatment is chemical fumigation with low cost, fast processing and easy application. However, due to concerns about health hazards of chemical pesticides and their resulting environmental pollution, other treatment methods have been conducted for controlling nut insects. These include ionizing radiation, controlled atmosphere, cold treatment, conventional hot air or water heating and novel radio frequency (RF) and microwave (MW) dielectric heating. Currently, the use of chemical fumigation remains widespread and the efficient use of RF and MW methods for nut insect control is still in research stage.

Comparison of the properties of these five methods has been reported as a review (S. Wang and J. Tang, 2001) where the last one method, dielectric heating using RF and MW energy, was proposed as an alternate, innovative quarantine treatment for nuts. Great effort and research are needed to overcome the problems associated with this new method, such as the high cost, the non-uniformity of heating and the damage to quality.

Chemical Fumigation:

Alternative control processes need to be developed to replace current treatment practices for both the domestic and international markets. It is a complex task to develop an effective thermal treatment that provides required quarantine security and simultaneously ensures minimum adverse effect on product quality.

Chemical fumigation has two distinct advantages for postharvest pest control in nuts: ease of use and low cost. Most postharvest pest management programs, therefore, rely heavily on fumigants, and most processing systems are designed to allow for fumigant treatments. Methyl bromide (MeBr) fumigation exposure of three hours considered short exposure time compared to hydrogen phosphide. MeBr used to control codling moths in cherries, nectarines, watermelons and in unshelled walnuts.

When used in commodity fumigation, MeBr gas is injected into a chamber or under a tarp containing the commodities. About 80 to 95% of the MeBr used for a typical commodity treatment eventually enters the atmosphere (USEPA, 1998).

MeBr has been identified by the U.S. Environmental Protection Agency (EPA) as having high ozone depletion potential (Anonymous, 1995). The U.S. has signed an international accord, known as the Montreal Protocol, to ban the use of MeBr in order to protect the Earth’s atmosphere. According to recent report from the congress (September 26th, 2007) MeBr is regulated for its potential ozone-depleting effects in the Earth’s stratosphere. Controls on production, emissions, and trade are mandated internationally under the 1987 Montreal Protocol on Substances that Deplete the Ozone Layer (the “Protocol”) and domestically under Title VI of the U.S. Clean Air Act (CAA).

However, the Protocol still regulates post-2004 production for critical uses. But U.S. agribusinesses have sought Critical Use Exemptions (CUE) from the EPA to treat commodities with MeBr after the ban. Production allowances for MeBr for 2005-2007 were approved under the Protocol and the EPA has approved allocation for registered users. Therefore, an alternative quarantine treatment is urgently required to replace this chemical fumigation.

Ionizing Radiation

Irradiation treatment is a process which exposes infested commodities to ionizing radiation so as to sterilize, kill, or prevent emergence of insect pests by damaging their DNA. This method includes three types of ionizing radiation used on foods: gamma rays from radioactive cobalt-60 and cesium-137, high energy electrons, and x-rays. The ability of gamma rays to deeply penetrate pallet loads of food makes it one of the most commonly used in post-harvest pest control. Some research showed that irradiation levels as low as 0.30 kGy were effective in controlling plum curculio, blueberry maggot, cherry fruit flies and codling moths, without altering overall fruit quality. Because these doses do not cause immediate kill of treated insects, a particular concern for radiation treatments is the possibility of inspectors or consumers finding live insects in the treated product.

Another issue with irradiation is the substantial initial investment per site to establish the facility, including a radiation shield control system and other auxiliary equipment. In order to be economically feasible, the facility must remain in continuous operation. However, the seasonal nature of nut and produce harvest prevents efficient use of facilities. Consumers also have concerns over the disposal of radioactive wastes, the safety of the irradiation technology and its effect on food (Wang and Tang 2001).

Controlled Atmosphere Treatments

Controlled atmosphere (CA) has been used for many years to extend commodity shelf life. CA has been used for the control of insects in stored grain and nut crops, and research has demonstrated its efficacy for fresh commodities. In general, O_2 concentrations must be below 1% and CO_2 concentrations must be above 20% for insect control. For most applications, however, CA treatments require long exposures. For example, to disinfest walnuts of navel orange worm two days of purging is required, followed by six days exposure to 0.5% O_2. This long treatment time may not be acceptable for some markets. To be able to certify and ship the quantities needed for the vital European market, optimal treatment time is 24 hours. In addition, prolonged exposure to low O_2 has detrimental effect on some fresh fruits (Wang et. al. 2000).

Cold Treatments

Chilled aeration has been used as a means to slow the development of insect pest populations within stored grains, and given sufficient exposure times, may effectively disinfest the product. Cold storage treatments have also been developed for quarantine purposes and for use against exotic fruit flies and other insects. Cold treatments may take several weeks to be effective, and thus work best when incorporated into existing storage or shipping regimes. Cold storage is an important component in existing quarantine treatments for codling moth on apple and has been combined with other treatments such as hot air and water heating.

While effective in some situations, the use of cold treatment is limited because of the lengthy treatment times required to kill insects, and the high costs associated with building and maintaining refrigerated storage. (Wang and Tang 2001).

Conventional Heating

Conventional heating methods are increasingly being used to provide an alternative treatment for chemical fumigation; these include forced hot air and hot water treatments. Since the heating mechanism is simple and the process can be easily controlled, many studies on various fruit types and insect species have been carried out using different thermal treatments alone or in combination with cold or controlled storage conditions. The fruit core must reach certain temperatures so that the treatment is effective even in the most insulated areas (such as inside nuts or into the center flesh, seeds and kernels). Slow heating rates by forced hot air or water results in a long treatment time.

Table 2 shows the heating time required to reach the core temperature, obtained by experiments with different medium temperatures, heating methods, and fruit types. Forced hot air is usually used to treat nuts because hot water heating results in unacceptable moisture content for storage, greater than 6% (Wang and Tang 2001). The core temperature is lower than the medium temperature and only reaches the target value after a long heating time. The heating duration required for the core to reach the medium temperature reported in Table 2 varies from 23 min to 360 min, which is mainly dependent on the fruit size (Wang et al., 2001b). Such heating methods are limited due to heat convection from the medium to the surface and heat conduction from the surface to the fruit core. Increasing the air speed and using small fruits can slightly decrease the heating time.

Table 2. Temperature characteristics of conventional heating methods (Wang and Tang 2001).

Medium temp., ℃	**Heating methods**	**Fruit types**	**Speed, ms-1**	**Core temp., ℃**	**Time required min**	**Sources**
40	Hot air	Apple	1	40	360	Whiting et al. (1999)
44	Moist air	Apple	2	42	97	Neven et al. (1996)
45	Hot air	Tangerine	2	44	60	Shellie & Mangan (1996)
45	Hot air	Cherry	2	44	23	Neven & Mitcham (1996)
48	Hot water	Small Potato	2	48	140	Hansen (1992)
48	Hot water	Large Potato	2	48	220	Hansen (1992)
48	Hot water	Grapefruit	2	48	155	Hansen (1992)
50	Hot air	Mango	2	48	150	Mangan & Ingle (1992)
52	Hot air	Mango	2.5	39	75	Sharp et al. (1991)
52	Hot air	Grapefruit	2	48	90	Shellie & Mangan (1996)

The slow heating process requires long treatment times in order to kill the insects. This heating method is limited due to the time required to heat the medium around the fruits then heat will be transferred by convection from medium to the surface and finally from surface to the fruit core by conduction. Furthermore, external and internal damage caused by heat over long exposure times included peel browning, pitting, poor color development and abnormal softening and prolonged heating may not be practical in industry applications. Therefore, RF and microwave (MW) heat treatments have been proposed to reach the same level of insect mortality in a shorter time (Wang and Tang 2001).

Dielectric Heating

Dielectric materials are those containing relatively few charge carriers like water molecules, so when the material is placed in an electrical field there is a displacement of charge and the material becomes polarized. If the electrical field is alternating, the displacement will follow the charges in the field direction. The material will therefore absorb energy from carrying out these displacements. This energy will dissipate out as heat, and the faster these displacements are, the larger energy will be dissipated. This technique is practical for industrial heating processes (Barber, H, 1983)

Dielectric heating occurs with both RF and microwave (MW) exposure. These are high frequency electromagnetic waves generated by magnetrons and klystrons. When a material containing water molecules is subjected to an electromagnetic field that rapidly changes direction, the water molecules rotate into alignment with the direction of the electrical field. The water molecular friction causes the internal heating of the material. A frequency in the range of 12 MHz-2450 MHz is usually used in food engineering. Dielectric materials, such as most agricultural products, can store electric energy and convert that electric energy into heat. The increase in temperature of a material by absorbed electromagnetic energy can be expressed by (Nelson, 1996):

$$\rho C_p \frac{\Delta T}{\Delta t} = 55.63 \times 10^{-12} f E^2 \varepsilon'' \qquad \text{Eq. (1)}$$

Where C_p is the specific heat of the material (J.kg^{-1}.°C^{-1}), ρ is the density of the material (kg.m^{-3}), E is the electric field intensity (V.m^{-1}), f is the frequency (Hz), ε” is the dielectric loss factor (s) of the material, Δt is the time duration (s) and ΔT is the temperature rise in the material (°C). From Eq. (1), the increase in temperature depends on the power, frequency, heating time and the material's dielectric loss factor. Higher temperatures in commodities can be achieved by long heating duration and high power input. If the dielectric loss factor is relatively constant, rapid dielectric heating using higher frequencies can be achieved with much lower field intensities. However, the frequency interacts with the dielectric loss factor where the dielectric loss factor variable is a function of the frequency, temperature and water content of the material.

Electromagnetic energy has been studied to control insects in commodities for many years. Initial investigations using RF heating to control pests of grain and nuts were conducted by Frings (1952), Thomas (1952) and Nelson (1966; 1973). Hirose et al. (1970) studied the use of dielectric heating (2450 MHz) to control tobacco moth larvae.

A recent study demonstrated the possibility of using 2450 MHz MW to destroy woodworms by heating the larvae to 52-53 °C for less than 3 minutes (Andreuccetti et al., 1994). Hallman and Sharp (1994) summarized RF and MW treatments which destroyed selected pests in many postharvest food crops. Nelson (1996) summarized more than five decades of research on the susceptibility of various stored grain insect species to RF and MW treatments.

Table 3 briefly presents a selection of RF and MW treatments targeting various insects under different conditions and temperatures. Since the congested bands of RF and MW are already in use for communication purposes, the Federal Communications Commission (FCC) has allocated five frequencies for industrial, scientific and medical (ISM) applications: 13.56, 27.12 and 40.68 MHz for RF, 915 and 2450 MHz for MWs.

Higher temperatures were used for stored grain than for fruits. The product quality after RF and MW treatments was rarely examined. More recently, Ikediala et al. (1999) and Wang et al. (2001a) reported that MW and RF treatments might have particular advantages over conventional heating methods in treating cherries and walnuts because the desired level of insect mortality was achieved without quality damage.

Table 3: Reported RF and MW heat treatments for different products and insects at various temperatures. (Wang and Tang (2001))

Frequency, MHz	Temp., °C	Product (Insect)	Quality	Sources
27	56	Wheat (weevil)	No	Anglade et al. (1979)
	53	Walnut (codling moth)	Yes	Wang et al. (2001a)
40	80	Pecan (weevil)	No	Nelson and Payne (1982)
915	55	Cherry (codling moth)	Yes	Ikediala et al. (1999)
915 & 2450	50-60	Cheese (microorganism)	Yes	Herve et al. (1998)
2450	45	Papaya (D. dorsalis)	No	Hayes et al. (1984)
	50	Fruit (Fruit fly)	Yes	Sharp et al. (1999)
	57	Wood (woodworm)	No	Andreuccetti et al. (1994)
	80	Cereal (weevil)	No	Shayesteh & Barthakur (1996)
12000-55000	43-61	Wheat (weevil)	No	Halverson et al. (1996)

DIELECTRIC PROPERTIES AND PERMITTIVITY

The dielectric properties of biological materials are important in the research of microwave processing of foods and agricultural materials, and the destruction of insect pests in postharvest and stored products. Dielectric properties, among other parameters, are required to provide insight into the interaction between materials and microwave and RF energy during microwave and RF heating.

It’s essential to learn about the dielectric properties of any material before to be processed in the microwave regime (Metaxas, A. C. and Meredith, R. J., 1983). The property which describes the behavior of a dielectric under the influence of a high frequency field is the relative or complex permittivity, ε^*, which is defined by the following equation (Eq. 2):

$$\varepsilon^* = \varepsilon' - j\varepsilon''_{eff} \qquad \text{Eq. (2)}$$

where ε''_{eff} is the effective loss factor and includes the effects of conductivity. In other words permittivity is a complex quantity commonly used to describe the electrical properties that influence reflection of electromagnetic waves at interfaces and the attenuation of the wave energy within materials. The real part is expressed in terms of the dielectric constant (energy stored), which influences the electric field distribution and the phase of waves traveling through the material. Dielectric loss factor, which is the imaginary part, mainly influences energy absorption.

The relative permittivity values of agricultural and biological materials are generally influenced by frequency, temperature, density, salt content, moisture content and the state of moisture (frozen, free or bound), as well as the size and arrangement of the cell structure.

A dielectric could be any material that is an electrical insulator and becomes polarized when placed in electric fields. As mentioned before, for example it may be between the electrodes of a capacitor. When the electric field is alternating, successive distortion of the molecules causes heating. This thermal heating effect is known as dielectric hysteresis heating, dielectric loss heating, or dielectric heating for simplicity

(Roussy, G. and Pearce, J. A., 1995). The heat dissipation mechanism is extremely complex, and can be explained by the movement of electric charges due to the electric field within a given atom and at the limits between two heterogeneous environments. When the electrodes polarity is inverted, the charges of the atom or molecules (electrons and protons) are drawn in the opposite direction; these successive changes of direction cause heating. The higher the frequency of the electric field, the more intense the friction and the higher the heat dissipated.

In general, a distinction is made between RF dielectric hysteresis heating (in which the frequency is between 10 and 300 MHz) and MW heating (in which the frequency is between 300 to 30,000 MHz). Frequency range is the not the only difference between RF and MW, their respective characteristics are not identical either (Orfeuil, M. and Robin, A., 1987).

To develop a suitable quarantine treatment protocol we need information on the dielectric properties of both the host nuts or kernels and the insects to be controlled. However limited literature reports exist on the permittivities and/or dielectric properties of insects.

MATERIALS AND METHODS

Industrial radio frequency (RF) heating operating between 10 and 100 MHz has been successfully used in the food processing and textile industries. It involves direct interactions between dielectric materials, such as fruits and nuts, with electromagnetic waves to generate heat. Unlike conventional surface heating with air or water, this avoids heating limitations caused by airspaces or bulkiness of the product. Because of their different dielectric properties, RF may also heat insects faster than the surrounding nut (Wang et al., 2003). RF is classified as "non-ionizing" radiation because these frequencies produce insufficient energy to ionize water molecules, unlike higher levels of energy such as X-rays and gamma rays that can alter molecular structures. It is therefore regarded as a safe treatment that will be acceptable for consumers. RF treatments also meet organic labeling standards. The challenge with RF treatments has been lack of heating uniformity, which is particularly difficult for products with limited heat tolerance.

Peanuts in this research were obtained from the USDA-ARS, National Peanut Research Laboratory in Dawson, GA and kept at temperatures around 5 °C. Peanuts were then cleaned from just before RF experiments took place. A 200 g sample was taken before each heating run to measure the moisture content according to ASAE standard procedures (S410.1 FEB03).

RF System:

Figure 2. Photo of the actual RF heating machine.

The RF heating machine system used in this research is manufactured by Strayfield International Limited, Workingham, UK. It is A 6 kW, 27 MHz pilot-scale RF system (COMBI 6-S). Photo of the actual RF system is illustrated in Figure 2.

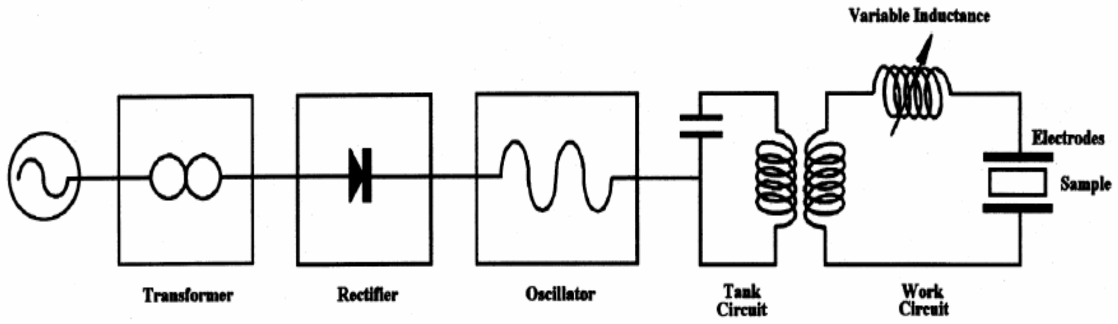


Figure 3: Schematic diagram of the RF heating system

Figure 3 shows a simple schematic diagram of the RF heating system. This system consists of a transformer, rectifier, oscillator, an inductance-capacitance pair commonly referred to as the ‘tank circuit,’ and the ‘work circuit.’ The transformer raised the voltage to about 9 kV, and the rectifier changed the alternating current to direct current. Direct current was then converted by the oscillator into RF energy at 27 MHz. This frequency was determined by the values of the inductance and the capacitor in the tank circuit. The parallel plate electrodes, with the sample placed in-between, acted as the capacitor in the work circuit. The gap of the electrode plates can be changed to adjust RF power, coupled to the sample between the two plates.

3500 g (3.5 Kg) of in-shell peanuts were placed in every RF run in a closed plastic container (30 X 20 X 15 cm) made of polyvinyl chloride (PVC). Air in the gap between the electrodes, and the plastic container did not heat during the RF treatment. The gap of the electrodes was adjusted to 6.12 cm to provide 0.4 kW of power. When RF waves are directed at peanut kernels infested with codling moth larvae, the absorption of RF energy depends on their dielectric loss factors. The difference between the dielectric properties of insects and the host material is important when considering the possibilities of preferential differential heating of insects.

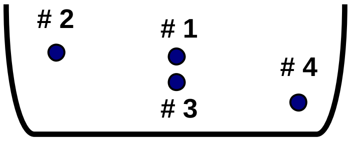


Figure 4. Locations of the four fiber optic temperature sensors in the plastic container.

Four fiber optic thermal sensors were used. Without cracking the peanut's shell, a small hole was drilled into the kernel through the shell, and sensors were inserted into the kernels. During each cycle, the four sensors were placed in the same positions in the plastic container. Figure 4 shows the fixed positions for each fiber optic sensor in the plastic container during each RF heating cycle.

Each plastic container held a 3500 g of in-shell peanut sample. The container is perforated on all sides to ensure the flow of heat out of the container; thus the peanuts around the walls have similar exposure as those in the middle.

Taking into consideration the uniformity of the dielectric properties of the products, the peanuts were placed into the container. During the experiments, the gap between upper and lower electrodes and the RF power source was unchanged. All the experiments were identical and repeated in the exact procedures in order to minimize any change in the dielectric properties during the RF heating runs/cycles and during the stirring/cooling cycles. Figure 5 (a) shows a picture of peanuts in the plastic container almost filled with 3500 g of peanuts with the 4 fiber optic probes inserted in their fixed positions. Figure 5 (b) shows a picture of the plastic container put in its fixed position between the upper and lower electrodes.

Figure 5 (a)

Figure 5 (b)

Figure 5(a). The RF Heating Container filled with 3.5 Kg peanuts.

Figure 5(b). The fixed position for upper and lower electrodes and the plastic container.

During RF heating, the kernel temperature of the peanuts was monitored using 4 fiber-optic probes/sensors. A small hole was drilled into the kernel through the shell without cracking the peanut’s shell. In every RF heating run the four probes were placed in the container in same positions; two probes in the middle (one in the bottom and one close to the surface), third probe close to one side, and each entered from a different side of the container. Experiments stopped when the coldest of the 4 monitored peanuts reached the target temperatures (40 °C, 50 °C or 60 °C). However, occasionally if the coldest sensor/probe indicated a very low increase in temperature, we ignored this reading and took the reading of the next coldest sensor into consideration.

Three treatment heating minimum temperatures of 40, 50 or 60 °C was applied during RF drying process. Each experiment consisted of 6 cycles of the RF heating/drying process and each cycle was followed by intermittent stirring and cooling using a laboratory fan at medium high speed for 20 minutes. The weight of the samples was taken just at the end of the stirring/cooling process.

The moisture measurement procedure is according to ASAE standards (S410.1 FEB03), where 200 g portions of peanuts were weighed, shelled, reweighed, and then put in a 130 °C oven for 6 hrs. The combined moisture calculation was completed immediately after removing each portion from the oven. Each heating/drying cycle lasts from 1.5 to 4 minutes according to the minimum heating temperature (40, 50 or 60 °C) and other factors. The heating cycles are followed by a 20 minute stirring and cooling cycle. The average air flow rate used in cooling cycle was around 3000 CFM. The dry air temperature was in the range of 22.0 to 25.6 °C and the wet air temperature was in the range of 17.3 to 21.4 °C. According to the wet and dry heat temperatures readings during all the experiments the relative humidity was in the range of 47% to 67% with the average relative humidity percentage of 60%.

The set of 6 cycles of RF heating (variable time) and 5 intermittent stirrings and cooling for 20 minutes was sufficient to overcome the non-uniformity due to differences in orientation, size and shape of shell, as well as the location of the shells in the drying container and to achieve the required peanut storage moisture content (less than 10.5% wet basis). In general, we found that the total average RF drying time is 10-11, 16-17 and 18-19 minutes for RF drying temperatures of 40, 50 and 60 °C respectively.

The average values of the RF treatment are stated in the table. The average heating time is for one complete RF cycle, i.e. 6 RF heating cycles with 5 intermittent stirring cycles.

RESULTS AND DISCUSSION

Non-uniformity of RF heating of peanuts:

During RF heating we observed a non-uniform heating for peanuts due to the difference in orientation, size and shape of the shells, whether the shell is opened or not, as well as the location of shells in the drying plastic container.

According to Wang, S. et al., (2004) 6 cycles of RF heating followed by intermittent stirring and cooling was sufficient to overcome the non-uniformity of peanuts. According to our results, for higher peanut internal drying temperatures, longer times were required to reach the temperature during RF treatments.

Figure 6(a)

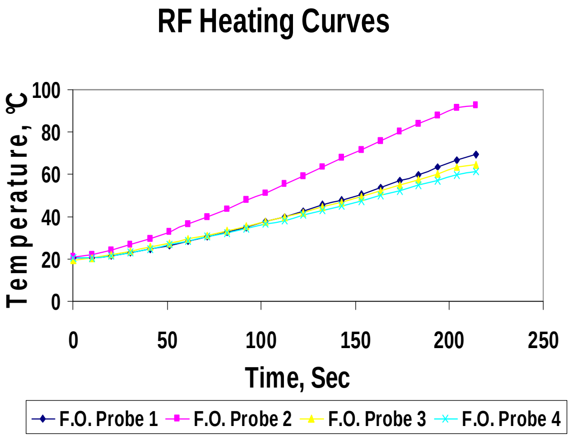


Figure 6(b)

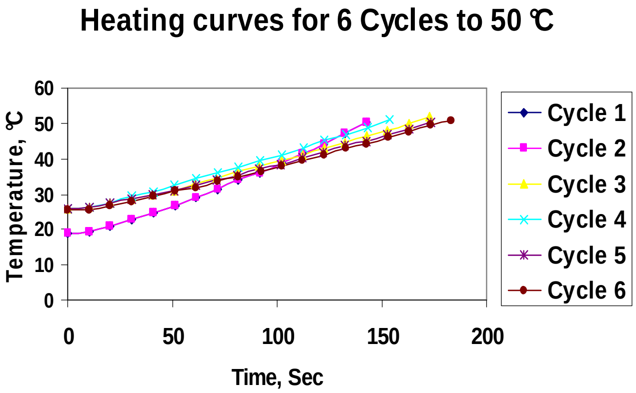


Figure 6(a). The four fiber optic probe temperature readings at 50 °C RF heating.
Figure 6(b). RF heating curves at 50 °C for six consecutive cycles.

Figure 6(a) shows the heating curves for one RF cycle of four peanut shells at different positions in the plastic container, those curves are simply the readings of the four fiber optic temperature sensors. As we can notice from this Figure (6(a)), the greatest difference of two probe temperature readings was around 30 °C.

Figure 6(b) shows the RF heating curves at average temperature of 50 °C for the six consecutive cycles. The probe position was fixed in all these six cycles. Comparing the differences between the highest and lowest temperature readings in this figure to those in Figure 6(a) we will find that differences are lower here. This means the difference in peanut temperatures in the same cycle due to the different positions of shells in the plastic container are higher than the differences of temperature reading for shells in the same positions even at different RF cycles. In other words, non-uniformity of RF heating due to the position of shells in the plastic container is the main reason for non-uniformity.

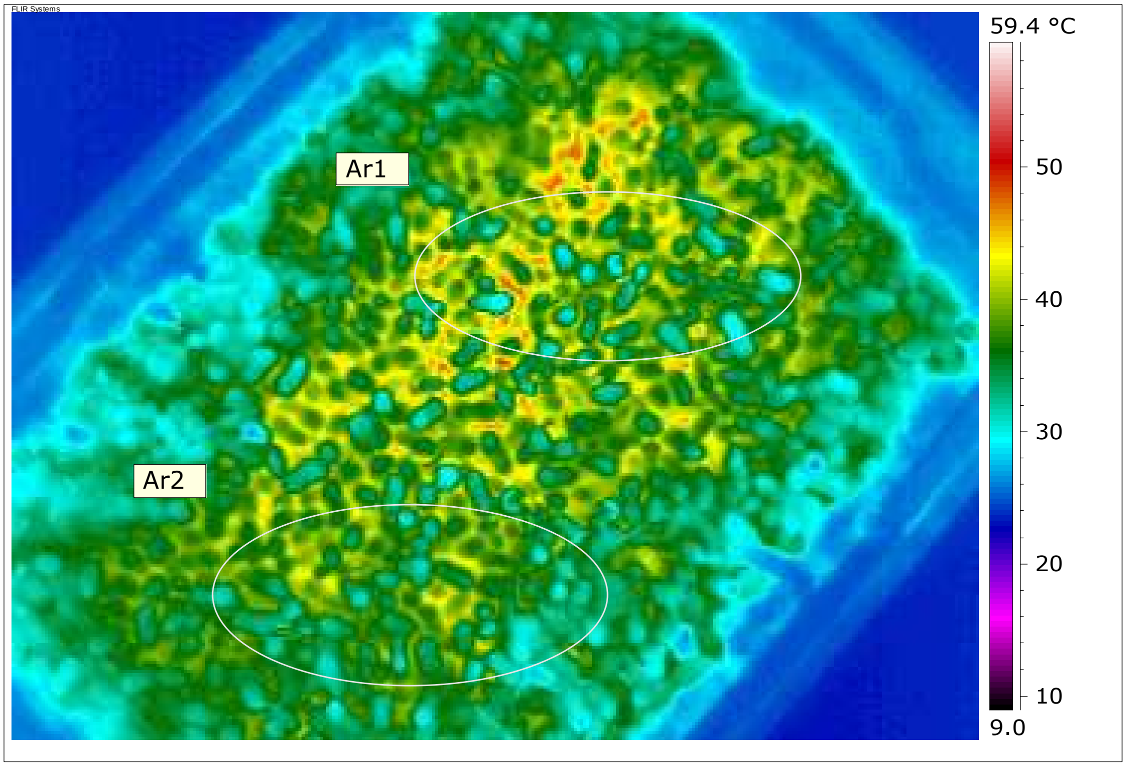


Figure 7. Thermal image of typical peanut shells temperature distribution immediately after RF heating cycle at 40 °C.

Thermal images have been taken immediately at the end of RF heating cycle at 40 °C for 2-3 minutes. Figure 7 shows infrared image of typical peanuts shells temperature distribution of peanuts right after the ending of RF. The shells around the corners and edges are easy to be cooled and dissipate their heat out than those in the middle or deep close to the bottom of the plastic container. Temperatures of those shells are less than those inside or to the bottom of the plastic container as it appears in Figure 7. In another experiment where the targeting heating temperature was 50 °C we took a thermal image directly at the end of the RF heating cycle for those shells in the middle and bottom of the plastic container and we measured the highest temperature in the media between these shells. This temperature was 65.5 °C as shown in Figure 8 and it represents the cursor on line Li1.

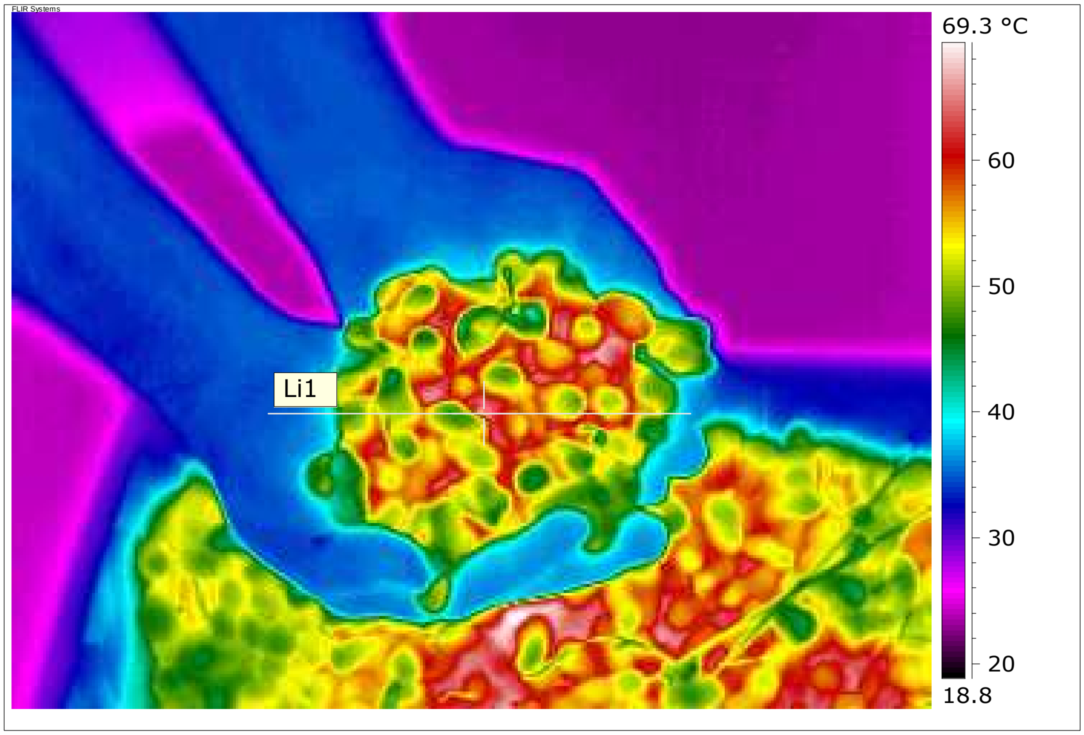


Figure 8. Thermal image present handful of peanut shells in middle and bottom of the plastic container for RF heating cycle at 50 °C.

The blue color represents the plastic container and two hands. The purple color represents the media outside the plastic container, and other colors represent the shells and media inside the plastic container. These temperatures measured by infrared imaging camera characterize the media, or hot air, in between the shells or the shells' temperatures, but not the temperature inside the shells or kernels. The difference is 15.5 °C between the media temperature and the targeted dehydration temperature (50.0 °C).

Apparently, in all the infra red pictures, the temperature of the media outside the shell is higher than the shells due to the fact that water vapor or steam is capable to further respond with RF and evolve heat while transferring from the kernels and shells to the media outside. This will lead us to expect temperature profile differences between the media, on the shells, inside the shells, and inside the kernels.

It was observed from these thermal images that overheating and less heating existed in many spots in the plastic container, hence the repeated stirrings and cooling cycles is needed to overcome heating non-uniformity.

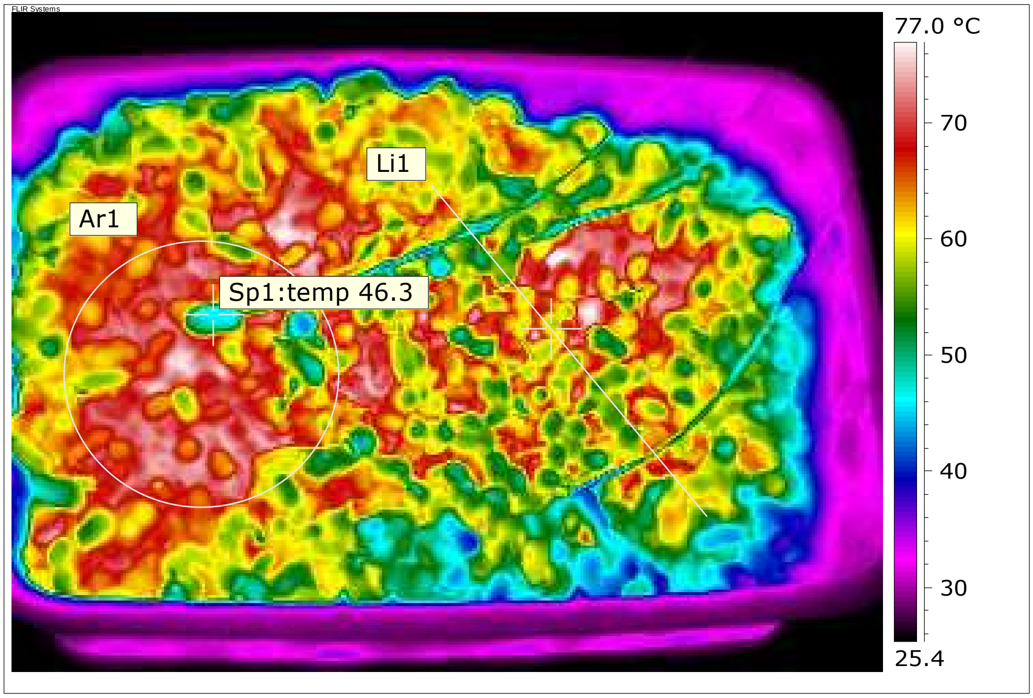
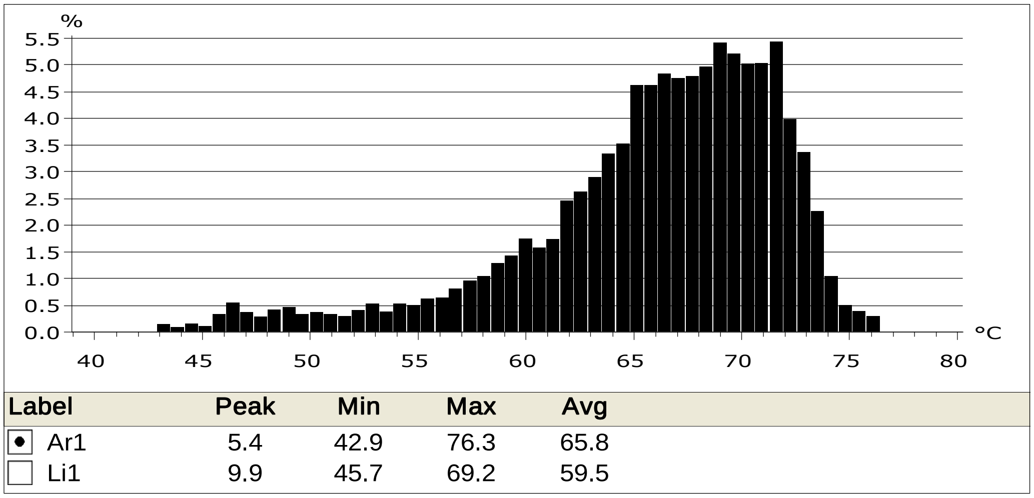
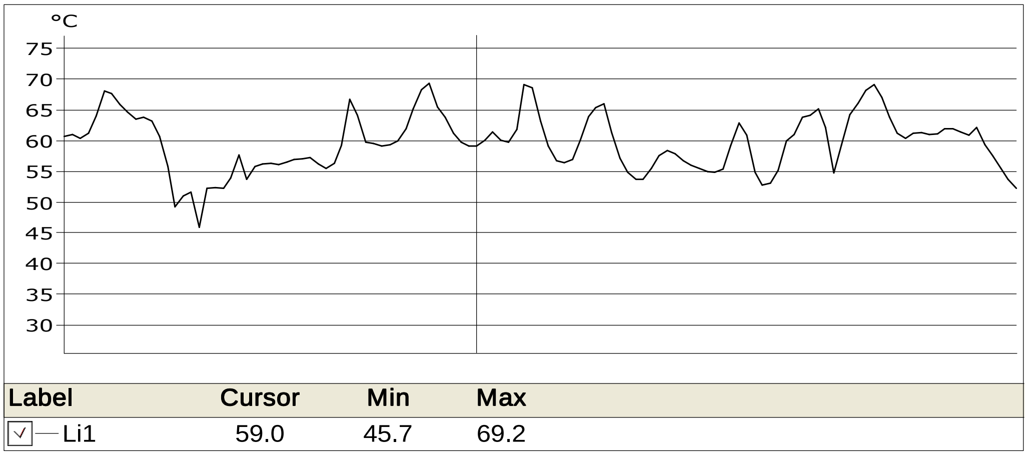


Figure 9. Thermal image of peanut shells temperature distribution at the end of RF heating cycle at 60 °C.



Label	Peak	Min	Max	Avg
● Ar1	5.4	42.9	76.3	65.8
☐ Li1	9.9	45.7	69.2	59.5

Figure 10(a). Statistical analysis results for the circle (Ar1) in Figure 9.



Label	Cursor	Min	Max
☑ —Li1	59.0	45.7	69.2

Figure 10(b). Statistical analysis results for the line (Li1) in Figure 9.

Figure 9 represents the temperature distribution for peanuts shells just at the end of RF heating cycle with targeting dehydration temperature at 60 ºC. The hot spots represent temperature above 65 ºC in the media between the shells and the average temperature of the shells is around 60 ºC. The single point temperature reading in this Figure is 46.3 and represents the temperature of one single shell in the spot circle with highest temperature; maximum temperature in this circle is 76.3 ºC as shown later.

Statistical analysis has been carried out using these infrared images. In Figure 9, we selected one circle spot area (Ar1) and one line (Li1) to extract some statistical numbers. Those statistical results are shown in Figure 10 (a & b). The average temperature in the circle (Ar1), minimum temperature and maximum temperature are 65.8, 42.9 and 76.3 ºC respectively as shown in Figure 10 (a). The peak for this circle (Ar1) was 5.4%. For the line (Li1) the average temperature, minimum temperature, and maximum temperature are 59.0, 45.7 and 69.2 ºC respectively as shown in Figure 10 (b). Figure 10 (a) shows skewed temperature profile toward the higher temperatures; in the range of 65 – 75 °C, with average peaks in the range of 2.5-3% per one RF Heating cycle, while the percentage of spots with temperature lower than 60 ºC are less than 10% and those spots higher than are less than 25%. However the spot temperatures do not represents the shells' or kernels' temperatures.

Generally, the non-uniformity of peanuts or nuts is due to many factors, including but not limited to the following:

- Difference in peanut orientation in the heating container
- Differences of size and shape of shells
- The location of shells in the drying container
- The wet and dry bulb temperature during the treatment
- Difference in the initial moisture content of peanuts
- The variety of peanut type, different harvesting time and planting locations

The proposed idea to overcome this non-uniformity problem is to use multiple numbers of RF treatments and intermittent stirrings. A set of cycles of RF treatment with intermittent stirring was used to dry peanuts to different final temperatures as will be described later in this research.

Applying RF treatment for a large or industrial scale will be applicable once the non-uniformity problem is resolved. The non-uniformity problem was also found in treating walnuts using a pilot-scale RF treatment protocol (Wang et al., 2003).

Figure 11 (a)

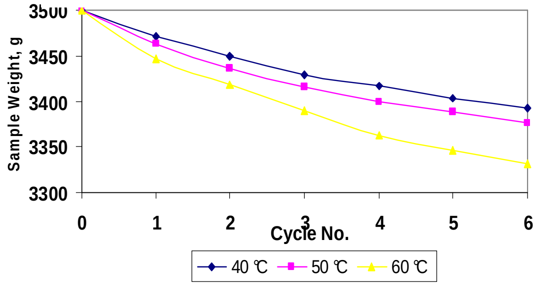


Figure 11 (b)

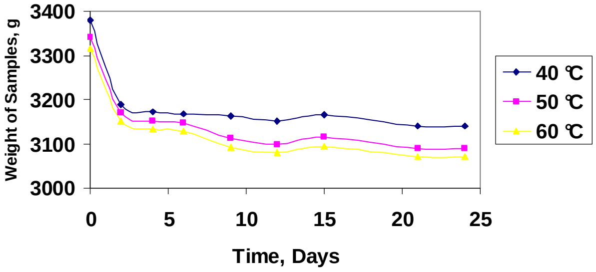


Figure 11(a). Decrease in sample weight through the six RF heating cycles.

Figure 11(b). Sample weight decrease after RF treatment.

After RF heating/drying treatment, we measured the moisture content and found that the peanuts moisture decreased over time. However, this total weight loss during RF heating is not yet adequate to reach the required storage percentage moisture content (M.C.). The number of RF dehydration/stirring-cooling cycles should be increased to reach the desirable M.C. percentage. In fact, RF treated peanuts reach this required M.C. within couple of days if stored in suitable environmental conditions. In our case we left RF treated peanuts samples in the lab for more than three weeks. These peanuts RF treated samples reached the required storage M.C. (11 %) after 2-3 days. This can be seen from the graph (Figure 11 (a)).

Equilibrium moisture content analysis for peanuts in this research was measured according to ASABE standards (ASAE S410.1 DEC97). Procedures of this standard based on shelling 200 g. of peanuts and weighing each portion (shells and kernels) separately then oven drying them in separate metal containers for 6 hours at 130 ± 3 °C.

Table 4. Average RF dehydration results

RF Heating Average Temperature		40 °C	50 °C	60 °C
Total Average RF Heating Time,	Sec.	638	979	1112
	Min.	10.6	16.3	18.5
Total Average Weight Loss After RF Process,	g.	110	163	196
Average Time per one Cycle of RF Process,	Sec.	107	163	214
	Min.	1.78	2.72	3.56
Total Average M.C. decrease,		3.68%	4.64%	5.98%

Table 4 represents the average results of eight RF heating experiments for each treatment temperature [40, 50, 60 °C]. The total average time required to reach the average dehydration temperatures using the standard 6 RF cycles was measured and shown in the table. Each RF cycle is followed by a stirring and cooling cycle for at least 15 minutes.

We can summarize the experiments results as follow:

In order to dry peanuts using the standard 6 RF heating cycles at average drying temperature of 40 °C we need to use the RF energy machine for about 10.6 minutes. In case we need to run the RF energy machine at average temperatures of 50 and 60 °C we will run it for a total of 16.3 and 18.5 minutes respectively. However this total time is the average of adding each time of the 6 RF heating cycles. The average time for each cycle is as shown in Table 4.

Using the RF energy machine for these total average times will decrease the peanuts shell weight about an average of 3.68%, 4.64% and 5.98% for the three dehydration temperatures 40, 50, and 60 ºC respectively.

These above-motioned average results are the summary of a total of 24 different experiments each consisting of standard 6 RF heating/cooling cycles. Table 5 shows the entirety of the 24 experiments and their data.

Appendix A shows all the experiments' date: peanuts type, heating temperature, maximum temperature difference (MTD) reading between 2 of the 4 total fiber optics channels during the 6 runs for each experiment, maximum average temperature (MAT) during the whole 6 runs for each experiments, total treatment/ RF heating period for the 6 RF heating runs (TTT/6 runs), average treatment time per single RF heating run (AHT/run), percentage initial moisture content (IMC), percentage final moisture content (FMC), percentage water evaporated or weight loss at the end of the experiments (%EW), dry air temperature (DAT), and wet air temperature (WAT).

From these results we can construct a graph representing the percentage weight loss in peanuts after the end of each complete RF treatment experiment. That would represent the amount of water evaporated by applying RF energy. This percentage value is variable and depends on many factors; these factors include but are not limited to the following:

- Initial peanut moisture content

- Type and harvesting time of peanuts
- RF heating/treatment average temperature (40, 50, 60 °C)
- Dry and wet air temperature

The lowest initial moisture content in all 24 experiments was 15.24% and the highest was 24.92%. However, the difference in percentage total water evaporated right after the end of RF treatment for these lowest and highest initial moisture contents ranged from 0.8 % in the case of 40 C average treatment temperature to 1.0 % in the case of 60 C average treatment temperature. In general and when other factors remained unchanged, the higher the initial moisture content the higher the RF loss factor thus the higher the percentage water evaporated from peanuts.

Figure 12 shows the percentage water evaporated from the peanuts at the end of each RF treatment experiment. The big triangular points on the chart represent the average percentage weight loss or evaporated water at each average RF treatment temperature. These values are 3.68%, 4.64% and 5.61% for RF treatment temperature 40, 50, and 60 °C respectively. These results clearly show that increasing the RF treatment temperature by 10 °C increases the percentage water evaporated by approximately one or 1.0%.

The total RF treatment time for the 6 runs for each RF treatment temperature is represented in Table 5. The difference in time is mainly due to the difference in peanut types and initial moisture contents.

Table 5. Total RF heating/drying time for eight different experiments at the three RF heating temperatures.

RF Treatment Temp., C	RF Total Heating Time for 6 runs, (Sec)							
40	525	526	736	689	859	665	568	539
50	860	951	1002	1171	984	941	964	956
60	1067	1270	1427	1511	1293	1261	1227	1265

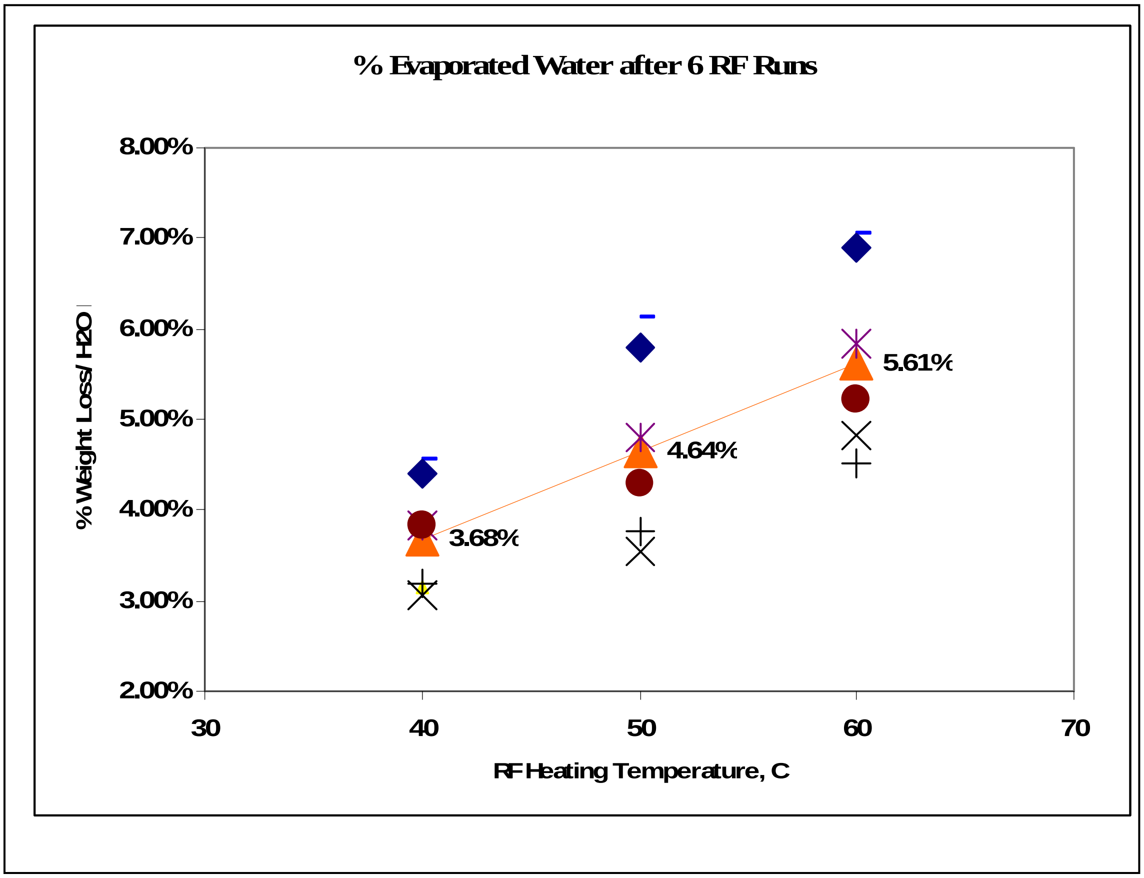


Figure 12. Percentage water evaporated after RF 6 treatment cycles.

Table 6 shows the percentage total weight loss or evaporated water at the end of the six RF treatment cycle for eight different experiment days. According to these percentages, the higher the treating temperature is the higher the percentage of water evaporated.

Table 6. Percentage total evaporated water after the six RF cycles

RF Treatment Temp.	% Water Evaporated at end of the 6th run of RF treatment							
40	3.46%	3.14%	3.05%	3.83%	3.83%	3.20%	4.55%	4.40%
50	4.54%	4.29%	3.54%	4.80%	4.29%	3.77%	6.12%	5.80%
60	5.26%	5.26%	4.83%	5.83%	5.23%	4.51%	7.06%	6.89%

Average values for the total amount of water evaporated, total treatment time after the end of the sixth RF treatment cycle and the average treatment time per run at different RF treatment temperatures are shown in Table 7.

Table 7. Average percentage water evaporated and times for RF treatment.

RF Treatment Temp.	Averages at the end of RF Treatment 6 runs			
	H_2O Evaporated	TTT (Sec.)	TTT (Min.)	TT / run (Sec.)
40	3.68%	638	10.6	106
50	4.64%	979	16.3	163
60	5.61%	1290	21.5	215

The rate of cooling for peanuts is slow and smooth compared to the rate of heating obtained form application of RF energy. Figure 13 shows the four fiber optic temperature readings during the RF cycle at average temperature of 50 °C, followed by natural cooling after stopping the RF machine. From the results in this figure (Figure 13) we noticed that it took more than 40 minutes for peanut temperature to decrease an average of 10 °C without applying forced cooling. This supports the need for forced cooling using a fan in order to reduce the duration of the cooling and stirring period. 15-20 minutes is sufficient to ensure equal exposure of peanuts to the cooling fan, such that the temperature decreases to a value between 22 and 30 C depending on the RF treatment temperature and the number of cycles in the overall RF treatment process.

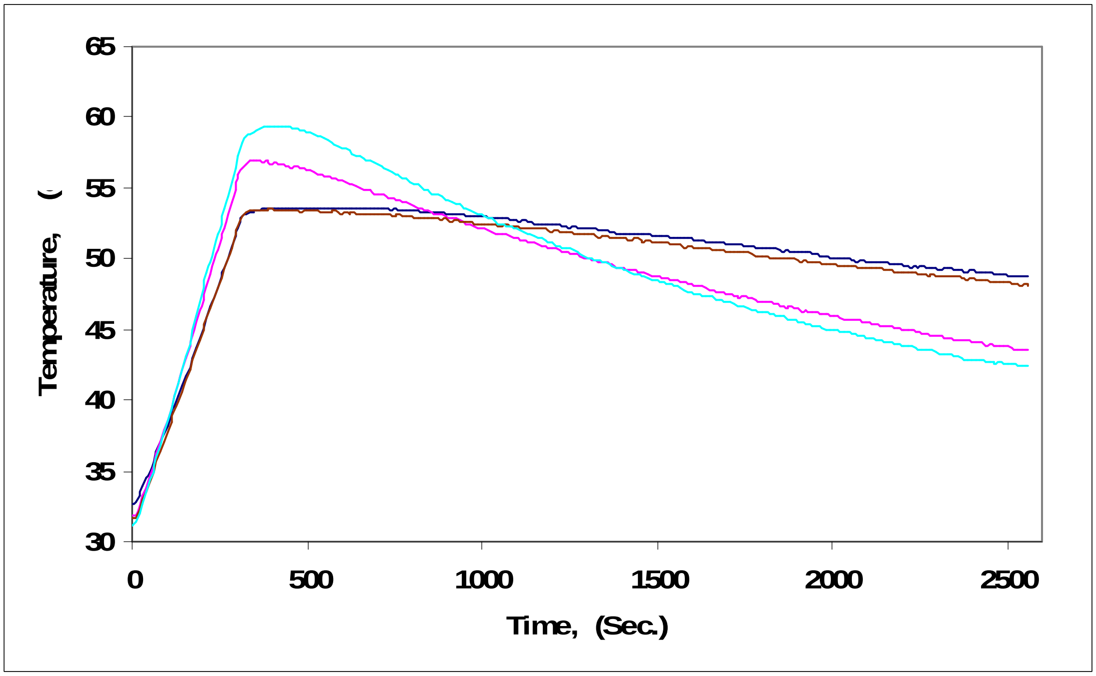


Figure 13. Natural decrease in peanut kernels temperature immediately after the end of a RF heating cycle at 50 °C.

After RF treatment the M.C. is still higher than that required for storage (11%) Increasing the number of RE heating/stirring-cooling cycles will decrease the M.C. in peanuts and will increase the probability of killing the insects and over come the non-uniformity problem.

However, peanuts continue losing moisture after the RF treatment for about a month as we mentioned above. The rate of weight loss is relatively high in the subsequent several days (2-3 days) after the RF treatment drying process then tends to be very slight after one week. It is important to mention here that the moisture content of peanuts is affected by many other outside factors such as the temperature in the environment and the humidity in the air.

THERMAL DEATH KINETICS OF RED FLOUR BEETLE (COLEOPTERA TENEBRIONIDAE)

INTRODUCTION

A major problem in the storage and marketing of peanuts is infestation by a variety of postharvest pests. This includes field pests of possible phytosanitary importance such as navel orangeworm, Amyelois transitella (Walker), and codling moth, Cydia pomonella (L.), as well as common stored-product pests such as Indian meal moth, Plodia interpunctella (Hübner), and red flour beetle, Tribolium castaneum (Herbst). Currently, the dried fruit and tree nut industry relies on fumigation with methyl bromide and phosphine (hydrogen phosphide) for postharvest insect control. Regulatory actions against methyl bromide (UNEP, 1992) and hydrogen phosphide (EPA, 1998), as well as insect resistance to hydrogen phosphide, may make these fumigants costly or unavailable to the nut industry. In addition, as the organic industry expands, the need for nonchemical postharvest insect control methods increases.

Although non-chemical treatments for postharvest dried fruits and nuts have been investigated in the past, few have been implemented. Recent concerns over resistance, regulatory action and the needs of the organic industry have generated a renewed interest in developing alternative treatments (Johnson et. al., 2004). There are other non-chemical alternatives methods to control postharvest insects such as: ionizing radiation, cold storage, controlled atmospheres, and combination treatments. All have disadvantages including substantial capital investment, extensive alteration of existing facilities, lengthy treatment times, or concerns over consumer acceptance. Heat treatments using forced hot air also have been proposed, but the lengthy exposure times, exceeding one hour, required to heat nuts throughout may substantially reduce product throughput and/or quality or cause product damage (Johnson et al. 2003).

Preferential heating of insects in nuts and fruits using RF is a promising thermal treatment procedure to control insects without affecting product quality. As mentioned before, post-harvested nuts and fruits are treated by chemical fumigation to control field and storage pests before being shipped to domestic and international markets. And because of the increasing public concern about adverse impacts of chemical fumigation on humans and the environment, there is a heightened interest in developing non–chemical pest control methods, especially thermal methods. An important key to developing successful thermal treatments is to balance the need for a complete kill of insects with a minimal thermal impact on product quality. (Tang et al. 2005)

The hypothesis of using RF to kill insects in nuts depends on the loss factor of the insects being 1.4 to 1.7 times greater than that for dry nut and fruits with 27- MHz RF energy (Wang et al. 2003).

Researchers at Washington State University have proven this result for walnuts and codling moth larvae (Wang et al. 2002a). The most common insect in peanuts in southern states is Red Flour Beetle (RFB), (Tribolium Castaneum), (Herbst). This insect is one of the most common existing in grain products while are stored. It is one of the most annoying pests in retail grocery stores and warehouses. RFB is very similar to confused flour beetle (Tribolium confusum) that first noted in the United States in 1893. Both insects occur throughout the world but the confused flour beetle is most abundant in the northern part of the United States, while the RFB is not commonly found north of the forty-first parallel. In general the RFB seems to be les common (Metcalf and Flint, 1962). On the other hand it is important to confirm that the insect in this research is the RFB and that could be strong reasons why our results are different from those have been published before. The two insects may be distinguished in the adult stage by minor differences, such as distance between the two eyes and the shape of the antennae (Metcalf and Flint, 1962).

The Industrial radio frequency heating system, extensively used in the food, textile, and wood processing industries, has been suggested for the control of postharvest insects and may avoid the problems associated with overheating and incomplete kill by providing more rapid product heating (10-20 °C /min). Recently, radio frequency treatments have been shown to kill codling moth and navel orangeworm found inside in-shell walnuts (Wang et al. 2001, 2002a).

In order to develop thermal treatment using MW or RF heating we proposed to study the thermal death kinetics for targeted insects first. Methods used for studying thermal death kinetics of insects include directly exposing insects in a water bath for specific times, heating insects in submerged tubes in a water bath, or heating insects in fruits (Johnson *et al.* 2003). Washington State University (WSU) developed a heating block system (Ikediala *et. al.* 2000 and Wang *et al.* 2002b). The system directly heats exposed insects and provides precise heating rates in the range from 1 to 20 °C /min.

This heating block system was used to determine thermal death kinetics of fifth instars of codling moth, naval orange-worm, and Indian meal moth (Johnson *et al.* 2003).

In this study we used the WSU heating system to identify the two most heat tolerant life stages: adults and old larvae, of red flour beetle according to Johnson *et al.* 2003, and to determine its thermal death kinetics at a heating rate of 15 °C /min.

MATERIALS AND METHODS

Heating Block System:

The WSU heating block system (Figure 14) consisted of top and bottom aluminum blocks (each 254 by 254 by 18 mm), heating pads, an insect test chamber, and a data acquisition/control unit (Ikediala *et al.* 2000 and Wang *et al.* 2002b). Calibrated type-T thermocouples inserted through sensor paths were used to monitor the temperatures of the top and bottom blocks. Heating rate, set-point temperature, and exposure time were computer controlled by a customized Visual Basic program and PID controllers via a solid-state relay (i/32 temperature & process controller, Omega Engineering Inc., Stamford, CT).

Figure 14. Heating block system.

Experiment Insects:

The Department of Entomology at Auburn University, AL. Prof. Henry Fadamiro was the sources of the red flour beetle. The red flour beetle used in these experiments was from a long-term laboratory culture maintained on a mixture of wheat bran and wheat flour. Cultures were kept in 0.5-1 liter glass canning jars at 25 °C and 50% RH. Two life stages were used in these experiments: adults and older larvae. Larvae age was in the range of 2-4 weeks. A control sample of 30 adults or older larvae was always maintained under the same conditions for more than two weeks after the experiments took place. The number of these adults and older larvae in the control plastic Petri dishes was monitored simultaneously with those used for the experiments. The experimental and control insects in the Petri dishes were kept with enough food and under suitable conditions to remain alive for at least two weeks after the experiments took place.

Experimental Protocol:

The heating rate chosen in this study was 15 °C/min to simulate the rapid heating of nuts subjected to radio frequency and microwave energies and to be comparable to other research results on the same insects (RFB).

Heating experiments took place for three different exposure temperatures (48, 50 and 52 °C) with three different time durations: 20, 30, and 40 minutes for 48 °C, 4, 8; 12 minutes for 50 °C and 0.5, 1; and 2 minutes for 52 °C. Approximately 50 test insects of each stage were treated at each exposure temperature-time combination, including controls.

Control insects were placed in Petri dishes with enough nutrition for more than two weeks. After two weeks all the control insects were still alive. Same environment including nutrition, Petri dishes, and temperature was applied to insects exposed in the heating block.

The test was replicated three times, with a minimum of 200 insects treated at each exposure temperature-time combination.

Before starting each heating experiment, test insects were poured from the Petri dishes onto the bottom heating block, and then the top block was placed on the bottom block and the treatment program began. At the end of each exposure, test insects were quickly (within 10 seconds) transferred to plastic Petri dishes. Treated insects were held at 25 °C, and 50% relative humidity (RH) until evaluation. Evaluation consisted of observing the insects for signs of movement. Insects' larvae or adults were considered dead if no movement was observed.

The evaluation was conducted at four times: right after the end of each exposure; 12-24 hours after the exposure; four days after the exposure; and after two weeks of exposure.

RESULTS AND DISCUSSION

In this part RFB older larvae were exposed to a couple of different temperature-time combination runs in the WSU heating system. The number of older larvae used in each run, and those older remained alive after the run are counted and shown in Table 8. Table 8 shows the number of older larvae used in each run, those remained alive after 12-24 hours, those remained alive after four days, and those remained alive for more than two weeks, are all shown in Table 8.

Table 8. Number of live RFB older larvae after heating at different times

Exposure (Temp. & Time)	Starting Quantity	No. of live RFB Older Larvae			
		After Exp.	Next Day	After4 Days	After > 2 weeks
48°C 20 min					
Sample 1	53	38	52	52	50
Sample 2	55	40	53	52	50
Sample 3	55	41	53	51	49
48°C 30 min					
Sample 1	53	32	45	33	26
Sample 2	54	34	47	40	38
Sample 3	51	31	44	12	28
48°C 40 min					
Sample 1	51	22	33	25	17
Sample 2	51	19	25	22	19
Sample 3	53	21	32	25	20
50°C 4 min					
Sample 1	50	12	50	48	42
Sample 2	51	7	51	47	41
Sample 3	50	12	50	49	42

Exposure (Temp. & Time)	Starting Quantity	No. of live RFB Older Larvae			
		After Exp.	Next Day	After4 Days	After > 2 weeks
50°C 8 min					
Sample 1	52	1	45	30	25
Sample 2	55	2	46	28	26
Sample 3	50	0	41	27	25
50°C 12 min					
Sample 1	55	0	0	20	13
Sample 2	53	0	0	21	13
Sample 3	51	1	1	10	8
52°C 0.5 min					
Sample 1	50	6	46	47	47
Sample 2	50	5	49	49	48
Sample 3	50	3	50	49	48
52 °C 1 min					
Sample 1	50	0	49	46	45
Sample 2	50	0	50	45	44
Sample 3	50	0	41	35	35
52°C 2 min					
Sample 1	50	0	45	21	19
Sample 2	50	0	49	28	24
Sample 3	50	0	46	32	27
Control Sample 1	50	50	50	50	50
Control Sample 2	30	30	30	30	30

It was found that the number of live older larvae is hard to discover immediately after the heating run. They might be thermally shocked so they do not move for awhile, then they will retain their normal activities within time (12-24 hours). That’s why the number of live larvae increased in the second column in Table 8 despite the fact that after 4 days some of those showed activities after one day were not moving.

However, all the results after two weeks are completely different from those have been published before with similar experimental conditions (Johnson *et al.* 2003). The reasons for our different results could be due to the fact that these larvae pretend not to move to protect themselves after this thermal shock, or they need time to rehabilitate and restore their normal activities. In the case of 50 °C-12 minutes temperature-time combination and after 24 hours all larvae did not move but after four days 20-40% of them started to move. Also these RFB insects here in the south east of the US could be different in the way they resist the heat than those in north or west coast of the US. Table 9 shows the percentage of mortality of RFB older larvae at different exposure of temperature-time combination.

Table 9. Percentage of mortality of RFB older larvae at different temperature-time combinations.

Exposure (Temp. & Time)	**Mortality of RFB Older Larvae**			
	After Exp.	**Next Day**	**After 4 Days**	**After > 2 weeks**
48°C 20 min				
Sample 1	28.30%	1.89%	1.89%	5.66%
Sample 2	27.27%	3.64%	5.45%	9.09%
Sample 3	25.45%	3.64%	7.27%	10.91%
48°C 30 min				
Sample 1	39.62%	15.09%	37.74%	50.94%
Sample 2	37.04%	12.96%	25.93%	29.63%
Sample 3	39.22%	13.73%	76.47%	45.10%
48°C 40 min				
Sample 1	56.86%	35.29%	50.98%	66.67%
Sample 2	62.75%	50.98%	56.86%	62.75%
Sample 3	60.38%	39.62%	52.83%	62.26%
50°C 4 min				
Sample 1	76.00%	0.00%	4.00%	16.00%
Sample 2	86.27%	0.00%	7.84%	19.61%
Sample 3	76.00%	0.00%	2.00%	16.00%
50°C 8 min				
Sample 1	98.08%	13.46%	42.31%	51.92%
Sample 2	96.36%	16.36%	49.09%	52.73%
Sample 3	100.00%	18.00%	46.00%	50.00%

Exposure (Temp. & Time)	Mortality of RFB Older Larvae			
	After Exp.	Next Day	After 4 Days	After > 2 weeks
50°C 12 min				
Sample 1	100.00%	100.00%	63.64%	76.36%
Sample 2	100.00%	100.00%	60.38%	75.47%
Sample 3	98.04%	98.04%	80.39%	84.31%
52°C 0.5 min				
Sample 1	88.00%	8.00%	6.00%	6.00%
Sample 2	90.00%	2.00%	2.00%	4.00%
Sample 3	94.00%	0.00%	2.00%	4.00%
52°C 1 min				
Sample 1	100.00%	2.00%	8.00%	10.00%
Sample 2	100.00%	0.00%	10.00%	12.00%
Sample 3	100.00%	18.00%	30.00%	30.00%
52°C 2 min				
Sample 1	100.00%	10.00%	58.00%	62.00%
Sample 2	100.00%	2.00%	44.00%	52.00%
Sample 3	100.00%	8.00%	36.00%	46.00%

The runs results for the other life stage of RFB adults are shown in Table 10 with the exposure temperature-time combination for each run with the number of RFB adults used in the heating block run (experiment). Those adults remain alive directly after the run, and those adults remain alive 12-24 hours after the run, and those adults remain alive after four days of the run, then those adults remain alive for more than two weeks after the run.

Table 10 Number of live RFB adults after heating at different temperature-time combinations.

Exposure (Temp. & Time)	Starting Quantity	No. of alive RFB Older Larvae			
		After Exp.	Next Day	After 4 Days	After > 2 weeks
48° C 20 min					
Sample 1	54	32	51	52	41
Sample 2	52	28	51	51	47
Sample 3	53	34	52	53	52
48° C 30 min					
Sample 1	56	18	54	56	32
Sample 2	52	16	48	50	39
Sample 3	50	13	44	46	37
48° C 40 min					
Sample 1	51	8	28	30	7
Sample 2	52	11	41	44	24
Sample 3	53	12	48	51	31
50° C 4 min					
Sample 1	50	17	49	46	45
Sample 2	51	19	51	50	49
Sample 3	52	18	52	48	48
50° C 8 min					
Sample 1	48	1	47	38	32
Sample 2	50	0	49	34	30
Sample 3	52	3	51	43	38
50° C 12 min					
Sample 1	52	0	0	0	0
Sample 2	53	0	0	0	2
Sample 3	53	0	0	1	0
52° C 0.5 min					
Sample 1	52	5	50	50	48
Sample 2	53	9	53	51	50
Sample 3	54	11	46	46	46
52° C 1 min					
Sample 1	51	0	12	46	43
Sample 2	54	0	9	48	44
Sample 3	51	0	11	48	46

Exposure (Temp. & Time)	Starting Quantity	No. of alive RFB Older Larvae			
		After Exp.	Next Day	After 4 Days	After > 2 weeks
52°C 2 min					
Sample 1	52	0	3	20	20
Sample 2	55	0	0	10	10
Sample 3	53	0	1	30	27
Control Sample 1	50	50	50	50	50
Control Sample 2	50	50	50	50	50

We still can observe the same results we found for older RFB larvae in this case of RFB adults where the number of live insects/adults is different in each single run depending on the time after the run occurred. Those still alive after more than two weeks are more than the normal average numbers shown before in similar studies.

The percentage mortality values of live RFB adults right after the run, after 12-24 hours of the run, after four days of the run, and for more than two weeks are all shown in Table. 11.

Table 11. Percentage of mortality of RFB adults at different temperature-time combinations.

Exposure (Temp. & Time)	Mortality of RFB Adults			
	After Exp.	Next Day	After 4 Days	After > 2 weeks
48°C 20 min				
Sample 1	40.74%	5.56%	3.70%	24.07%
Sample 2	46.15%	1.92%	1.92%	9.62%
Sample 3	35.85%	1.89%	0.00%	1.89%
48°C 30 min				
Sample 1	67.86%	3.57%	0.00%	42.86%
Sample 2	69.23%	7.69%	3.85%	25.00%
Sample 3	74.00%	12.00%	8.00%	26.00%
48°C 40 min				
Sample 1	84.31%	45.10%	41.18%	86.27%
Sample 2	78.85%	21.15%	15.38%	53.85%
Sample 3	77.36%	9.43%	3.77%	41.51%

Exposure (Temp. & Time)	Mortality of RFB Adults			
	After Exp.	Next Day	After 4 Days	After > 2 weeks
50°C 4 min				
Sample 1	66.00%	2.00%	8.00%	10.00%
Sample 2	62.75%	0.00%	1.96%	3.92%
Sample 3	65.38%	0.00%	7.69%	7.69%
50°C 8 min				
Sample 1	97.92%	2.08%	20.83%	33.33%
Sample 2	100.00%	2.00%	32.00%	40.00%
Sample 3	94.23%	1.92%	17.31%	26.92%
50°C 12 min				
Sample 1	100.00%	100.00%	100.00%	100.00%
Sample 2	100.00%	100.00%	100.00%	96.23%
Sample 3	100.00%	100.00%	98.11%	100.00%
52°C 0.5 min				
Sample 1	90.38%	3.85%	3.85%	7.69%
Sample 2	83.02%	0.00%	3.77%	5.66%
Sample 3	79.63%	14.81%	14.81%	14.81%
52°C 1 min				
Sample 1	100.00%	76.47%	9.80%	15.69%
Sample 2	100.00%	83.33%	11.11%	18.52%
Sample 3	100.00%	78.43%	5.88%	9.80%
52°C 2 min				
Sample 1	100.00%	94.23%	61.54%	61.54%
Sample 2	100.00%	100.00%	81.82%	81.82%
Sample 3	100.00%	98.11%	43.40%	49.06%

The results shown before were for the three replicated runs of each exposure temperature-time combination. However, the average percentage mortality of these three replicated results is shown in Table 12.

Table 12. Average percentage of mortality of RFB older larvae and adults at different temperature-time combinations

Exposure, Temp. °C & (min)	RFB Older Larvae				RFB Adults			
	After Exp.	Next Day	After 4 Days	After 2 weeks	After Exp.	Next Day	After 4 Days	After 2 weeks
48 °C								
20	27.01%	3.05%	4.87%	8.55%	40.91%	3.12%	1.88%	11.86%
30	38.63%	13.93%	46.71%	41.89%	70.36%	7.75%	3.95%	31.29%
40	60.00%	41.97%	53.56%	63.89%	80.17%	25.23%	20.11%	60.54%
50 °C								
4	79.42%	0.00%	4.61%	17.20%	64.71%	0.67%	5.88%	7.20%
8	98.15%	15.94%	45.80%	51.55%	97.38%	2.00%	23.38%	33.42%
12	99.35%	99.35%	68.14%	78.72%	100 %	100%	99.37%	98.74%
52 °C								
0.5	90.67%	3.33%	3.33%	4.67%	84.34%	6.22%	7.48%	9.39%
1	100%	6.67%	16.00%	17.33%	100%	79.41%	8.93%	14.67%
2	100%	6.67%	46.00%	53.33%	100 %	97.45%	62.25%	64.14%

According to these results and after two weeks of the run or exposure temperature-time combination we found best treatment results at 48 °C -12 minutes combination with average percentage mortality of 78.72% for RFB older larvae and 98.74% for RFB adults.

One of RF applications is dehydration of peanuts but it could be also considered as a treatment procedure or pest control for FRB insects. After comparing these results in Table 12, we will realize that 40 °C RF treating temperature is completely not adequate pest control temperature or treatment protocol for RFB insects.

The average percentage mortality at 50 °C for both RFB older larvae and adults are the highest values according to our results. However, the total heating block time in this temperature-time combination was 12 minutes, while the total intermittent RF heating time was 16.3 minutes at 50 °C with an average of (16.3/6 =) 2.7 minutes per one RF heating cycle. This is completely different exposure time compared to the 12 minutes direct heating exposure in WSU heating block.

In addition to these results the quality of peanuts at 60 °C is not acceptable at least for most of fancy food application of peanuts according to the percentage of broken and shelled peanuts due to the excessive thermal treatment.

That means the RF treatment temperature should not be higher than 52 °C. However there is still a huge research area regarding both RF heating protocol and RFB pest control in peanuts. For example we need to investigate the quality of peanuts using RF heating/drying at 52 °C assuming that the results of dehydration will be very close to those at 50 °C.

During the RF treatment experiment, the temperature rise inside kernels is certainly different than the insect temperature due to the different loss factor. However the loss factor of insects is higher than of kernels and consequently the temperature of insects (with all life stages) is higher than the temperature inside kernels. This fact is hypothesis because there are other factors manipulate the heat transfer to the insects and those other factors need to be defined in the future research work

The question is whether or not the total RF heating time in 6 cycles will be a good pest control scenario.

It’s also important to mention that during weighing the different treated samples of peanuts for the couple of weeks after the RF treatment to check weight loss in the sample, we have seen very active alive RFB adults and some of them even flying out of the peanuts. This fact we have noticed was for all the samples, regardless of the treatment temperature. It is also important to report that those RFB insects (adults and larvae) used in WSU heating block experiments, and stayed alive after the experiments, did show activity for more than two weeks and some of them were re-productive.

CONCLUSIONS

We found that RF energy is a very economic alternative to conventional process for dehydration of peanuts. Energy and time required to dry peanuts using RF is negligible to the conventional process; we are comparing maximum use of RF machine of 30 minutes to couple of days of using conventional methods. This is due to the fact that heat is evolved from inside the peanuts in the dielectric properties in RF heating application.

However some difficulties face the use of this new method. Most of the difficulties are related to the non-uniformity of peanuts. This obstacle could be overcome using multiple RF heating/drying runs, each followed with intermittent stirring and cooling process for sufficient time.

Our recommendation is using a certain screening and/or sorting process in the industrial scale RF treatment of peanuts in which peanuts can be classified into groups of different sizes and types. This will help reduce non-uniformity problem. RF heating process is a straight line relation between time and target or treatment required temperature. Using RF energy for dehydration of peanuts will save time, and energy.

The thermal death kinetic for RFB insects needs a lot of attention in future research. Our results are different than those already published before. We found out RFB adults and larvae are resistant to RF energy; even at higher temperatures (60 °C).

The reason of resistance of RFB could be due to the fact that the mechanism of heat transfer in WSU heat block system to the RFB is different from that in RF energy heating. In other words, the heat gained by insects in WSU system is by heat conduction from heating elements through the whole experiment period. While in the real RF system the heat gained by insects is generated by the interaction between electromagnetic field and insects. Future research should be conducted to take this point into consideration before the RF energy is applied as a pest control of RFB in peanuts.

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APPENDIXES

APPENDIX A

Standard RF Heating/Cooling Cycles Results Data for 24 Experiments

Total of 24 RF treatment experiments have been performed according to our protocol to over come the non-uniformity problem, i.e. each experiment consist of 6 RF heating runs each followed by intermittent cooling and stirring run. Every 8 RF experiments have been performed at a different treatment temperature; 40, 50, or 60 °C.

A summary for all these experiments is illustrated, with all the results and experiment circumstances in the next table.

The abbreviations used in this table are as follows:

Peanut: Peanuts type used in the experiments, there are 3 main types.

MTD: Maximum temperature difference between any 2 fiber temperature optics readings during the RF heating run.

ATD: Average maximum temperature difference between any 2 fiber temperature optics readings during the RF heating run.

TTT/6 runs: Total treatment/heating time for the 6 runs, Seconds.

AHT/run: Average heating time per one single run, Seconds.

IMC: Initial percentage moisture content in peanuts.

FMC: Final percentage moisture content in peanuts after RF treatment cycles.

%EW: Percentage evaporated water, or % moisture content loss after RF treatment.

DAT: Dry air temperature, ˚C.

WAT: Wet air temperature, ˚C.

Exp.	Date	Peanut	RF H. Temp	MTD	AMTD	TTT/ 6 runs	AHT /run	IMC	FMC	% EW	DAT	WAT
1	10/6	Ga. green	40	36.3	18.9	525	88	19.32%	15.87%	3.46%	25.5	19.8
2	10/6	Ga. green	50	33.2	14.9	860	143		14.78%	4.54%		
3	10/6	Ga. green	60	37.5	20.2	1067	178		14.07%	5.26%		
4	10/7	Ga. green	40	44.7	23.4	526	88	18.00%	14.86%	3.14%	25.6	21.4
5	10/7	Ga. green	50	42.2	26.8	951	159		13.71%	4.29%		
6	10/7	Ga. green	60	49.4	39.3	1270	212		12.74%	5.26%		
7	10/10	Ga. green	40	30.9	14.1	736	123	15.24%	12.19%	3.05%	22	17.3
8	10/10	Ga. green	50	47.4	34.1	1002	167		11.70%	3.54%		
9	10/10	Ga. green	60	31.5	16.1	1427	238		10.41%	4.83%		
10	10/12	GA01R	40	49.7	35.2	689	115	24.92%	21.09%	3.83%	23.8	19
11	10/12	GA01R	50	46.3	33.8	1171	195		20.12%	4.80%		
12	10/12	GA01R	60	56.1	41.8	1511	252		19.09%	5.83%		
13	10/12	GA01R	40	38.1	23	859	143	22.08%	18.25%	3.83%	24.7	18.7
14	10/12	GA01R	50	55.3	36.1	984	164		17.79%	4.29%		
15	10/12	GA01R	60	50.7	35.8	1293	216		16.85%	5.23%		
16	10/13	GA01R	40	50.8	32.2	665	111	22.71%	19.51%	3.20%	23.2	18
17	10/13	GA01R	50	77.6	55.3	941	157		18.94%	3.77%		
18	10/13	GA01R	60	59.4	44.8	1261	210		18.20%	4.51%		
19	10/14	C99R	40	26.7	17.2	568	95	20.72%	16.17%	4.55%	24.5	18.7
20	10/14	C99R	50	31.1	16.7	964	161		14.60%	6.12%		
21	10/14	C99R	60	44.8	34.1	1227	205		13.66%	7.06%		
22	10/14	C99R	40	19.2	9.2	539	90	20.42%	16.02%	4.40%	24.7	17.8
23	10/14	C99R	50	46.3	33.1	956	159		14.62%	5.80%		
24	10/14	C99R	60	57.1	40.4	1265	211		13.53%	6.89%		

APPENDIX B

RF Heating Curves

The following charts present the complete set of RF heating cycles and/or experiments. Every chart represents one single RF heating cycle with 4 curves. Each consists of fiber optic temperature-time readings. The line in the bold black color represents trend line or he average values of temperature reading of these four channels.

We fitted the average temperature readings in straight line where intersection is the initial starting temperature inside the kernel at every RF heating run. Each RF treatment experiment consisted of 6 RF runs at an average temperature of 40, 50 or 60 °C as we mentioned before in this thesis, so every one page stands for the results of one complete RF experiment. We have eight complete experiments at each temperature with total of 24 complete RF experiments and 144 charts.

All the slopes of these trend lines (144 trend lines) have been gathered in to find the average slope. It has been found that 0.217 is the average value of the slopes of all the 144 trend lines, so that the following straight-line equation stands for the RF heating pattern for peanuts regardless the final required average heating temperature:

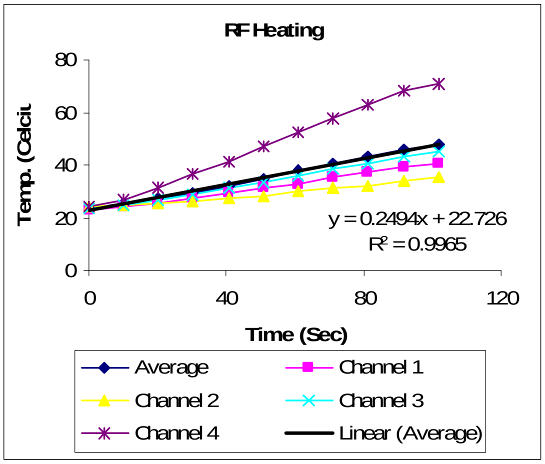
$$T = 0.217 \times t + T_{in}$$

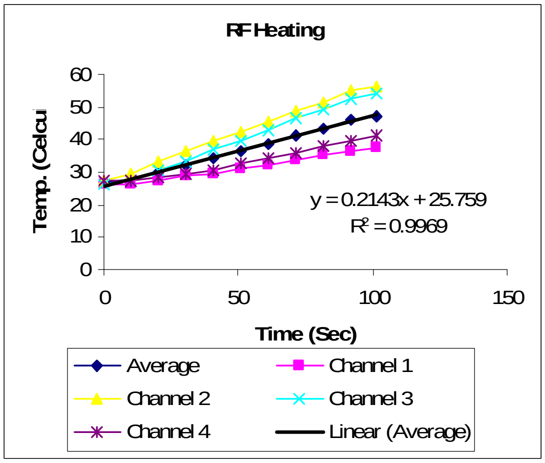
where:

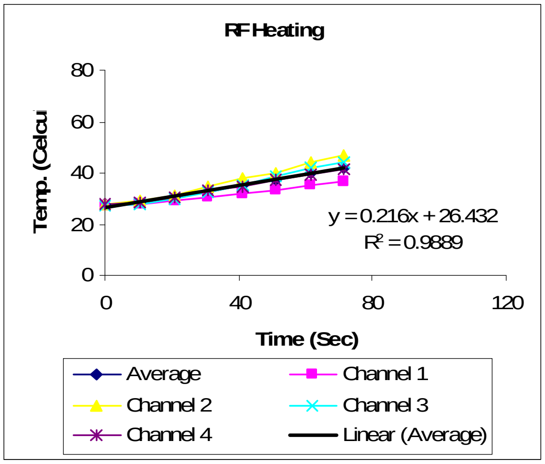
T: final temperature inside peanuts kernel after one RF heating run, °C

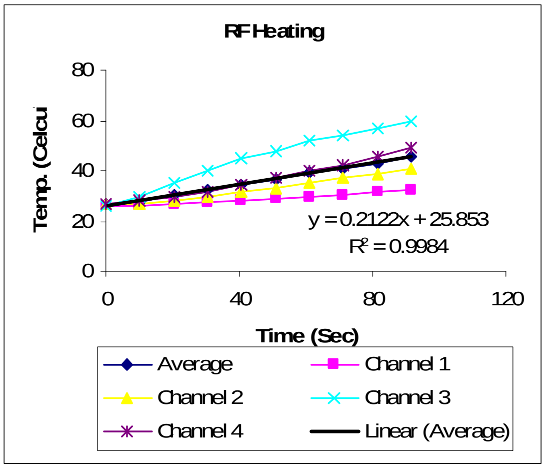
t: the run time, Sec.

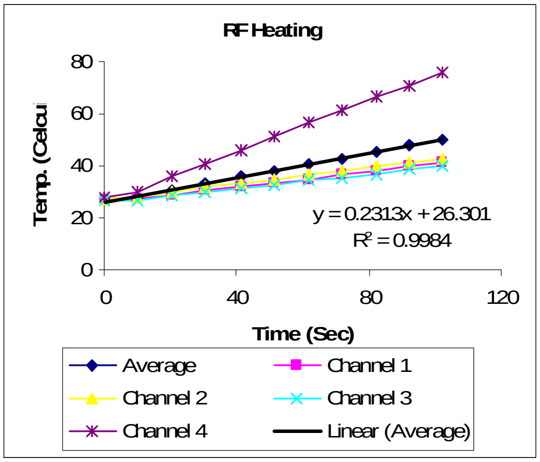
T_{in}: Initial temperature inside the peanuts kernel.

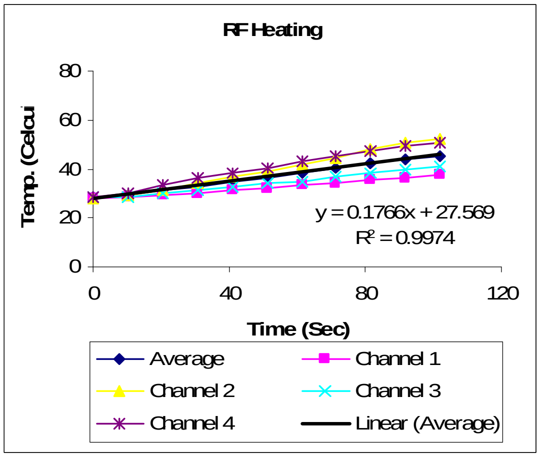

RF Heating
Temp. (Celci
80
60
40
20
0
0
40
80
120
Time (Sec)
y = 0.2494x + 22.726
R² = 0.9965
Average
Channel 1
Channel 2
Channel 3
Channel 4
Linear (Average)

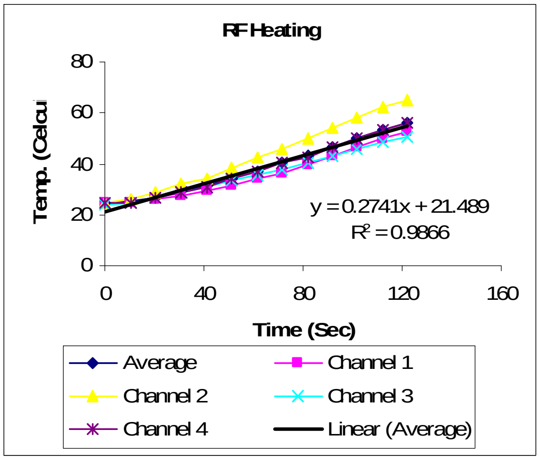

RF Heating
Temp. (Celcu
60
50
40
30
20
10
0
0
50
100
150
Time (Sec)
y = 0.2143x + 25.759
R² = 0.9969
Average
Channel 1
Channel 2
Channel 3
Channel 4
Linear (Average)

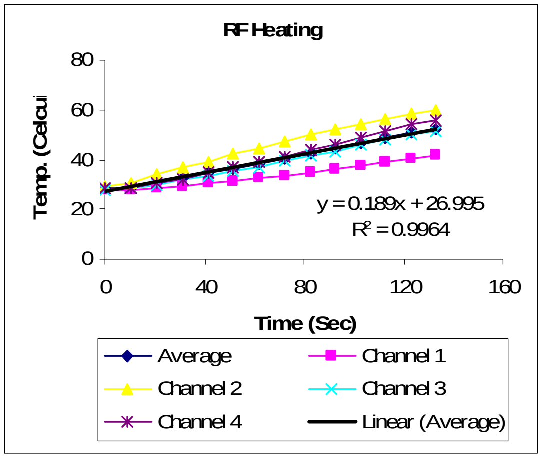

RF Heating
Temp. (Celcu
80
60
40
20
0
0
40
80
120
Time (Sec)
y = 0.216x + 26.432
R² = 0.9889
Average
Channel 1
Channel 2
Channel 3
Channel 4
Linear (Average)

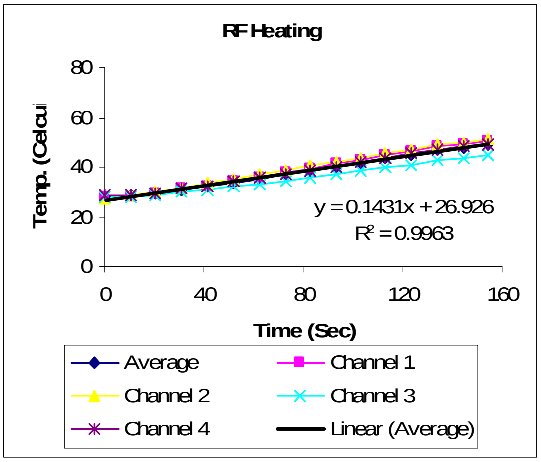

RF Heating
Temp. (Celcu
80
60
40
20
0
0
40
80
120
Time (Sec)
y = 0.2122x + 25.853
R² = 0.9984
Average
Channel 1
Channel 2
Channel 3
Channel 4
Linear (Average)

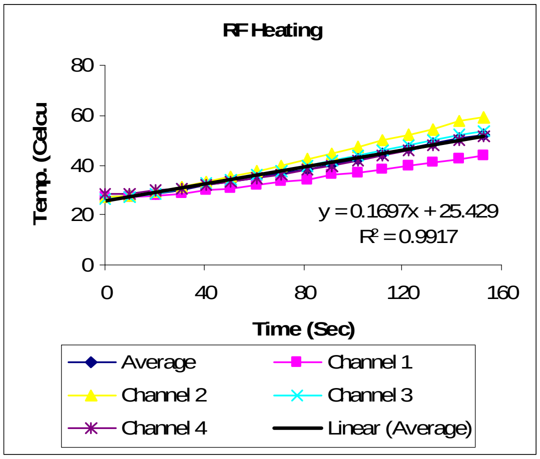

RF Heating
Temp. (Celcu
80
60
40
20
0
0
40
80
120
Time (Sec)
y = 0.2313x + 26.301
R² = 0.9984
Average
Channel 1
Channel 2
Channel 3
Channel 4
Linear (Average)

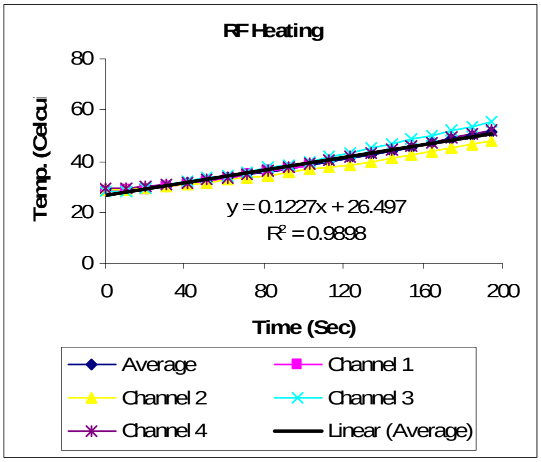

RF Heating
Temp. (Celcu
80
60
40
20
0
0
40
80
120
Time (Sec)
y = 0.1766x + 27.569
R² = 0.9974
Average
Channel 1
Channel 2
Channel 3
Channel 4
Linear (Average)

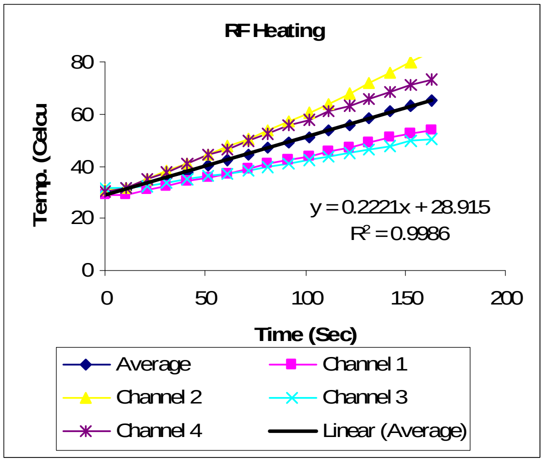

RF Heating
Temp. (Celcui
80
60
40
20
0
0
40
80
120
160
Time (Sec)
y = 0.2741x + 21.489
R^2 = 0.9866
Average
Channel 1
Channel 2
Channel 3
Channel 4
Linear (Average)

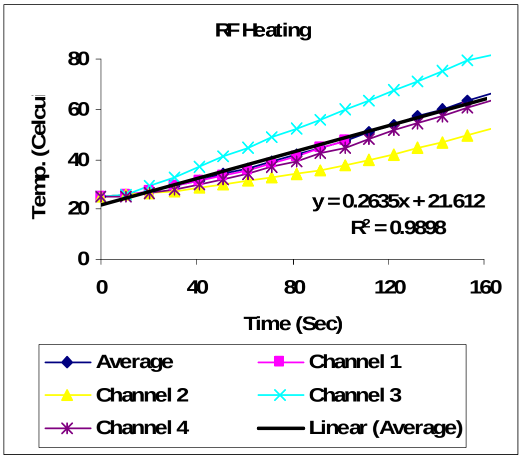

RF Heating
Temp. (Celcui
80
60
40
20
0
0
40
80
120
160
Time (Sec)
y = 0.189x + 26.995
R^2 = 0.9964
Average
Channel 1
Channel 2
Channel 3
Channel 4
Linear (Average)

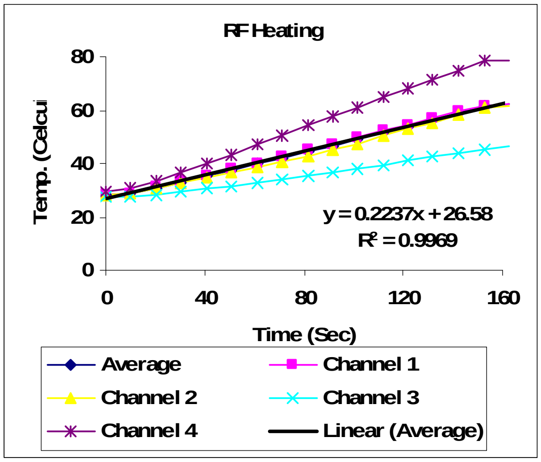

RF Heating
Temp. (Celcui
80
60
40
20
0
0
40
80
120
160
Time (Sec)
y = 0.1431x + 26.926
R^2 = 0.9963
Average
Channel 1
Channel 2
Channel 3
Channel 4
Linear (Average)

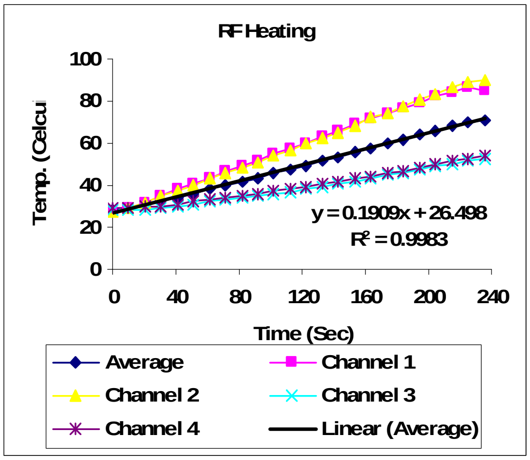

RF Heating
Temp. (Celcui
80
60
40
20
0
0
40
80
120
160
Time (Sec)
y = 0.1697x + 25.429
R^2 = 0.9917
Average
Channel 1
Channel 2
Channel 3
Channel 4
Linear (Average)

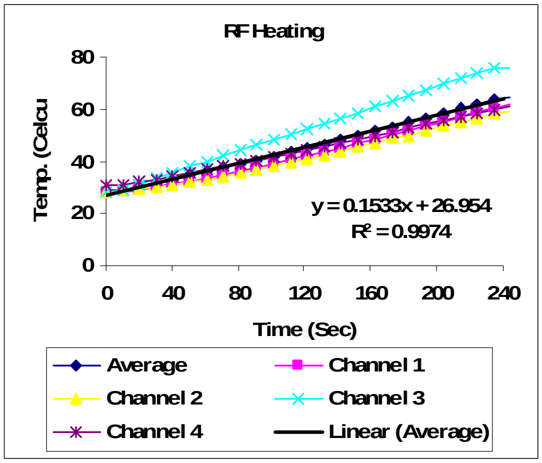

RF Heating
Temp. (Celcui
80
60
40
20
0
0
40
80
120
160
200
Time (Sec)
y = 0.1227x + 26.497
R^2 = 0.9898
Average
Channel 1
Channel 2
Channel 3
Channel 4
Linear (Average)

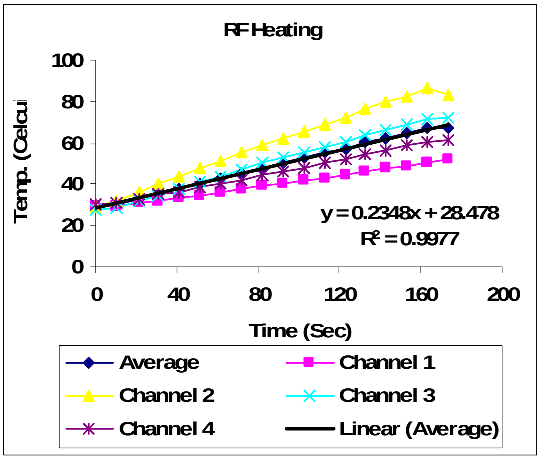

RF Heating
Temp. (Celcu
80
60
40
20
0
0
50
100
150
200
Time (Sec)
y = 0.2221x + 28.915
R^2 = 0.9986
Average
Channel 1
Channel 2
Channel 3
Channel 4
Linear (Average)

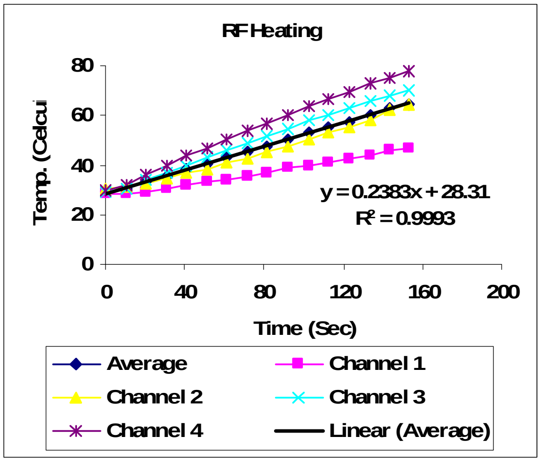

RF Heating
Temp. (Celcui
80
60
40
20
0
0
40
80
120
160
Time (Sec)
y = 0.2635x + 21.612
R² = 0.9898
Average
Channel 1
Channel 2
Channel 3
Channel 4
Linear (Average)

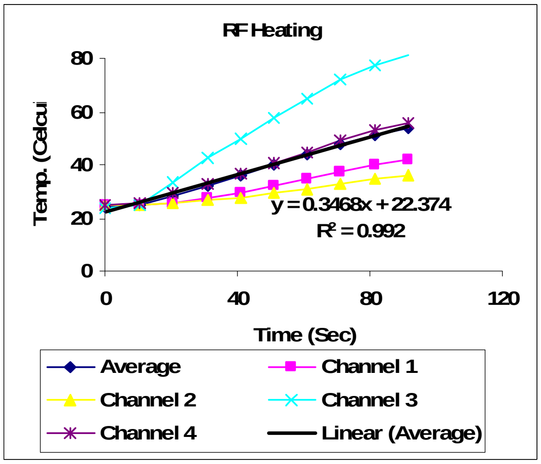

RF Heating
Temp. (Celcui
80
60
40
20
0
0
40
80
120
160
Time (Sec)
y = 0.2237x + 26.58
R² = 0.9969
Average
Channel 1
Channel 2
Channel 3
Channel 4
Linear (Average)

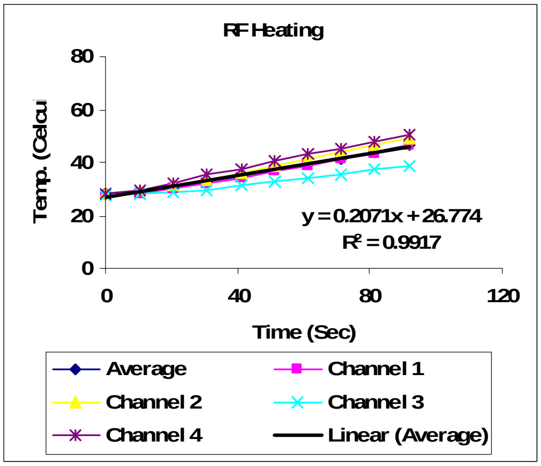

RF Heating
Temp. (Celcui
100
80
60
40
20
0
0
40
80
120
160
200
240
Time (Sec)
y = 0.1909x + 26.498
R² = 0.9983
Average
Channel 1
Channel 2
Channel 3
Channel 4
Linear (Average)

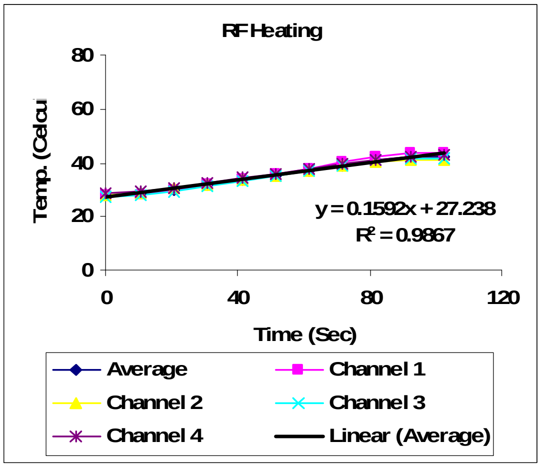

RF Heating
Temp. (Celcu
80
60
40
20
0
0
40
80
120
160
200
240
Time (Sec)
y = 0.1533x + 26.954
R² = 0.9974
Average
Channel 1
Channel 2
Channel 3
Channel 4
Linear (Average)

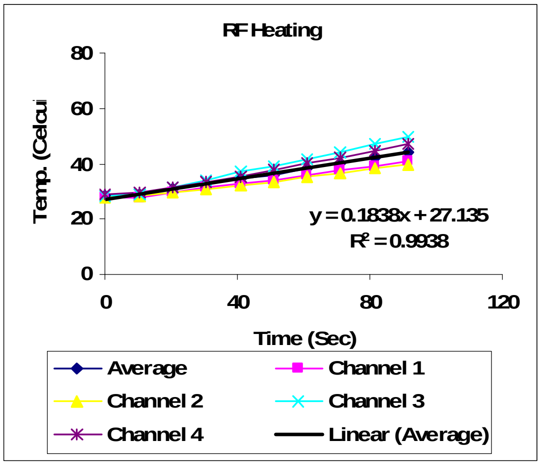

RF Heating
Temp. (Celcui
100
80
60
40
20
0
0
40
80
120
160
200
Time (Sec)
y = 0.2348x + 28.478
R² = 0.9977
Average
Channel 1
Channel 2
Channel 3
Channel 4
Linear (Average)

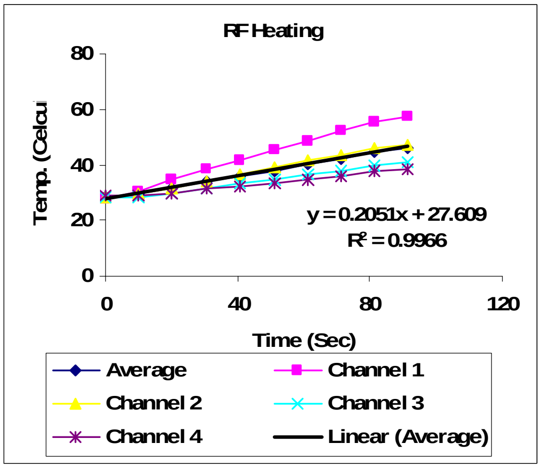

RF Heating
Temp. (Celcui
80
60
40
20
0
0
40
80
120
160
200
Time (Sec)
y = 0.2383x + 28.31
R² = 0.9993
Average
Channel 1
Channel 2
Channel 3
Channel 4
Linear (Average)

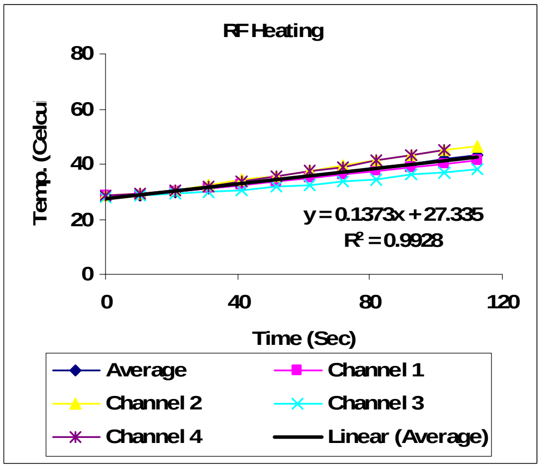

RF Heating
Temp. (Celcui
80
60
40
20
0
0
40
80
120
Time (Sec)
y = 0.3468x + 22.374
R² = 0.992
Average
Channel 1
Channel 2
Channel 3
Channel 4
Linear (Average)

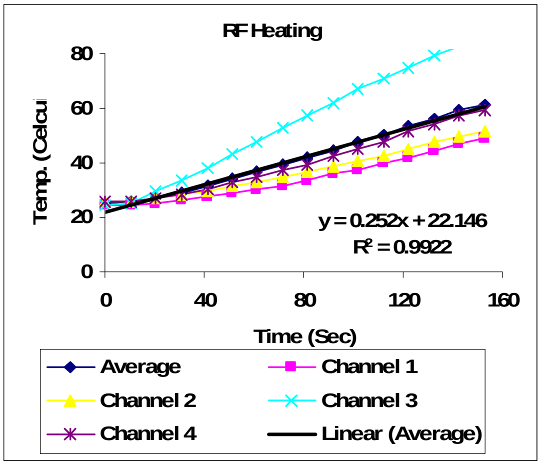

RF Heating
Temp. (Celcui
80
60
40
20
0
0
40
80
120
Time (Sec)
y = 0.2071x + 26.774
R² = 0.9917
Average
Channel 1
Channel 2
Channel 3
Channel 4
Linear (Average)

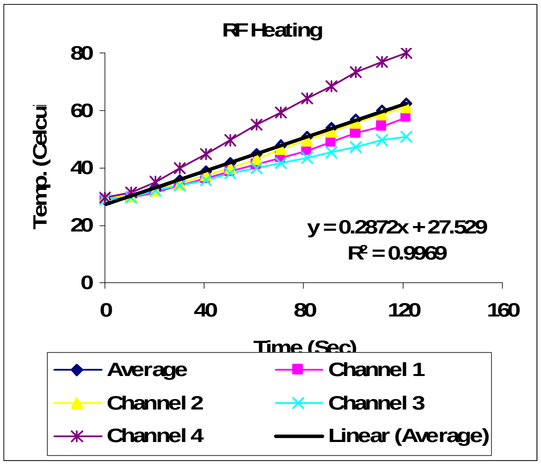

RF Heating
Temp. (Celcui
80
60
40
20
0
0
40
80
120
Time (Sec)
y = 0.1592x + 27.238
R² = 0.9867
Average
Channel 1
Channel 2
Channel 3
Channel 4
Linear (Average)

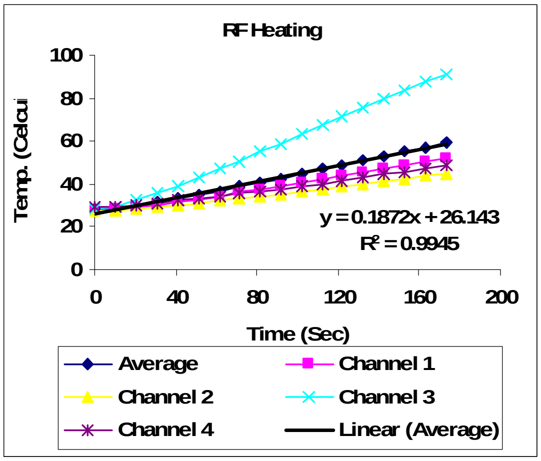

RF Heating
Temp. (Celcui
80
60
40
20
0
0
40
80
120
Time (Sec)
y = 0.1838x + 27.135
R² = 0.9938
Average
Channel 1
Channel 2
Channel 3
Channel 4
Linear (Average)

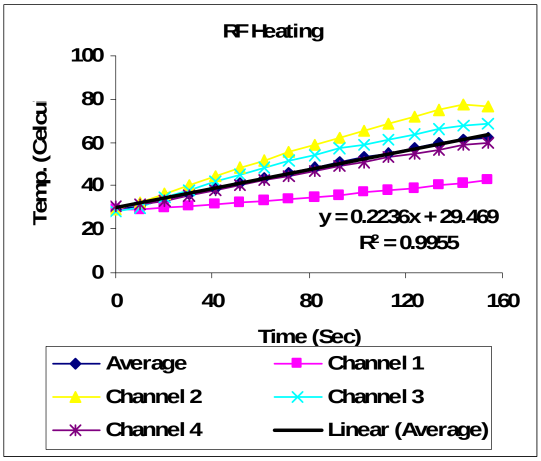

RF Heating
Temp. (Celcui
80
60
40
20
0
0
40
80
120
Time (Sec)
y = 0.2051x + 27.609
R² = 0.9966
Average
Channel 1
Channel 2
Channel 3
Channel 4
Linear (Average)

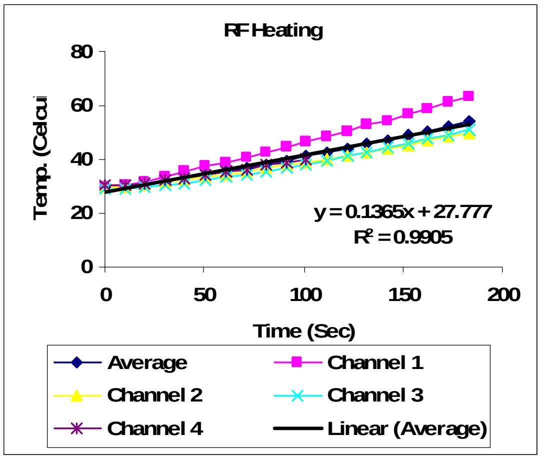

RF Heating
Temp. (Celcui
80
60
40
20
0
0
40
80
120
Time (Sec)
y = 0.1373x + 27.335
R² = 0.9928
Average
Channel 1
Channel 2
Channel 3
Channel 4
Linear (Average)

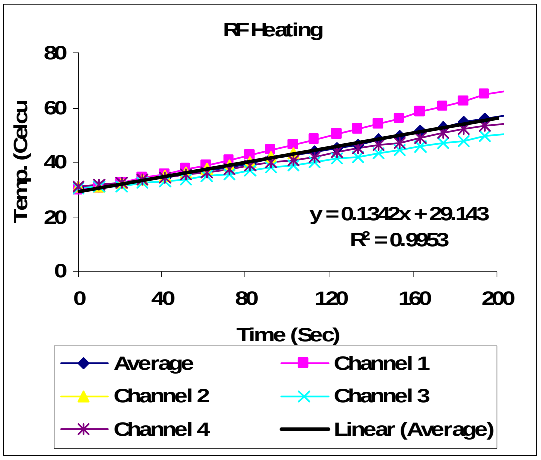

RF Heating
Temp. (Celcui
80
60
40
20
0
0
40
80
120
160
Time (Sec)
y = 0.252x + 22.146
$R^2 = 0.9922$
Average
Channel 1
Channel 2
Channel 3
Channel 4
Linear (Average)

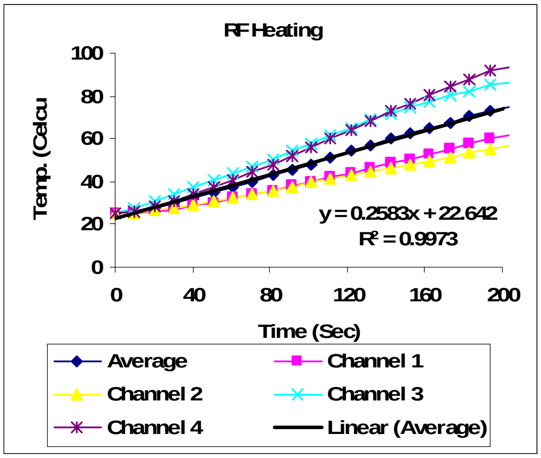

RF Heating
Temp. (Celcui
80
60
40
20
0
0
40
80
120
160
Time (Sec)
y = 0.2872x + 27.529
$R^2 = 0.9969$
Average
Channel 1
Channel 2
Channel 3
Channel 4
Linear (Average)

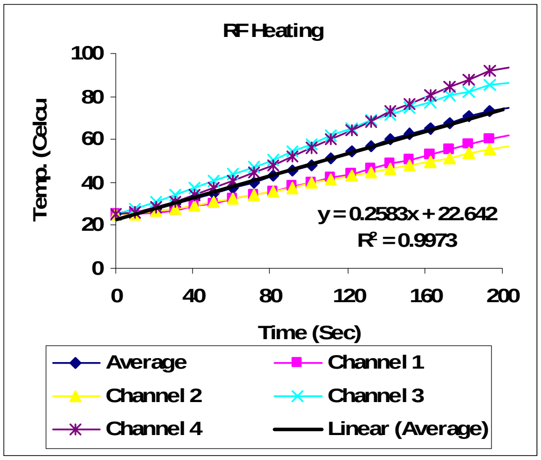

RF Heating
Temp. (Celcui
100
80
60
40
20
0
0
40
80
120
160
200
Time (Sec)
y = 0.1872x + 26.143
$R^2 = 0.9945$
Average
Channel 1
Channel 2
Channel 3
Channel 4
Linear (Average)

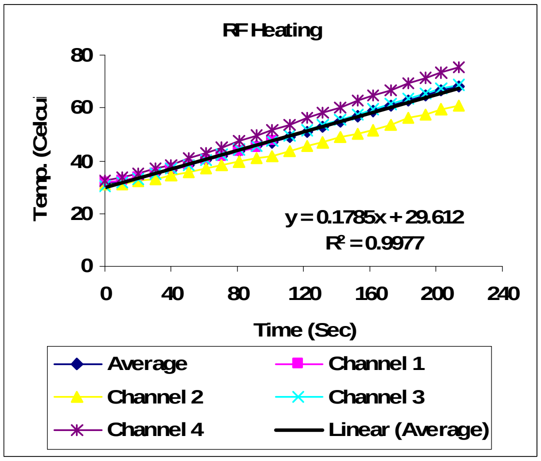

RF Heating
Temp. (Celcui
100
80
60
40
20
0
0
40
80
120
160
Time (Sec)
y = 0.2236x + 29.469
$R^2 = 0.9955$
Average
Channel 1
Channel 2
Channel 3
Channel 4
Linear (Average)

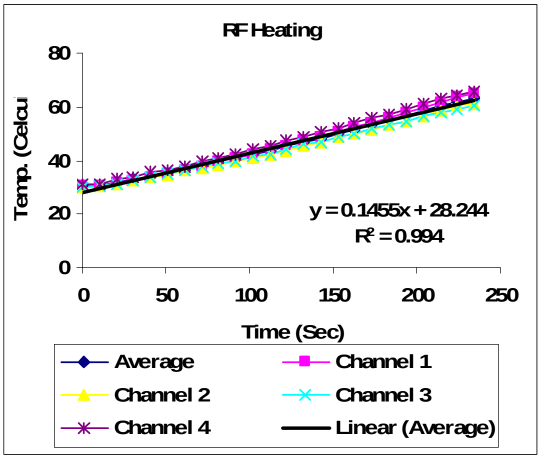

RF Heating
Temp. (Celcui
80
60
40
20
0
0
50
100
150
200
Time (Sec)
y = 0.1365x + 27.777
$R^2 = 0.9905$
Average
Channel 1
Channel 2
Channel 3
Channel 4
Linear (Average)

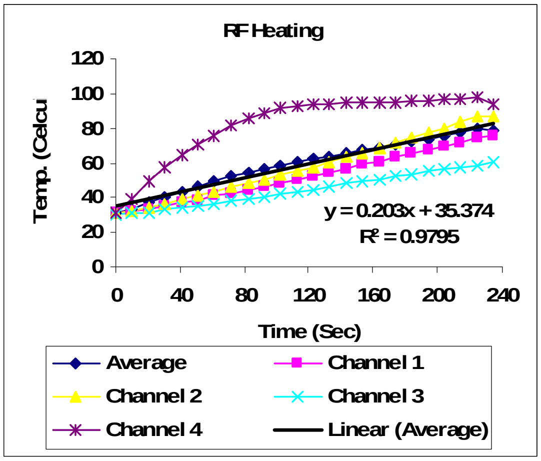

RF Heating
Temp. (Celcu
80
60
40
20
0
0
40
80
120
160
200
Time (Sec)
y = 0.1342x + 29.143
$R^2 = 0.9953$
Average
Channel 1
Channel 2
Channel 3
Channel 4
Linear (Average)

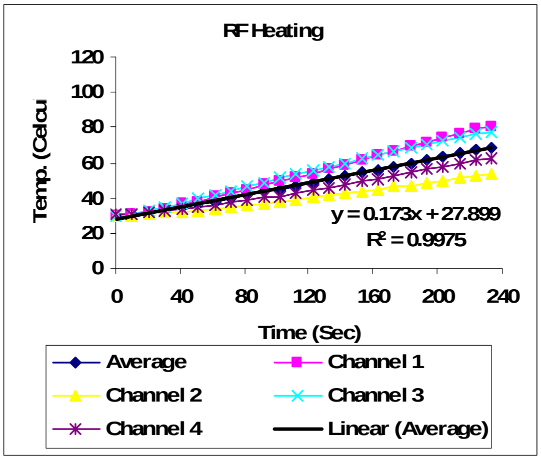

RF Heating
Temp. (Celcu
100
80
60
40
20
0
0
40
80
120
160
200
Time (Sec)
y = 0.2583x + 22.642
R^2 = 0.9973
Average
Channel 1
Channel 2
Channel 3
Channel 4
Linear (Average)

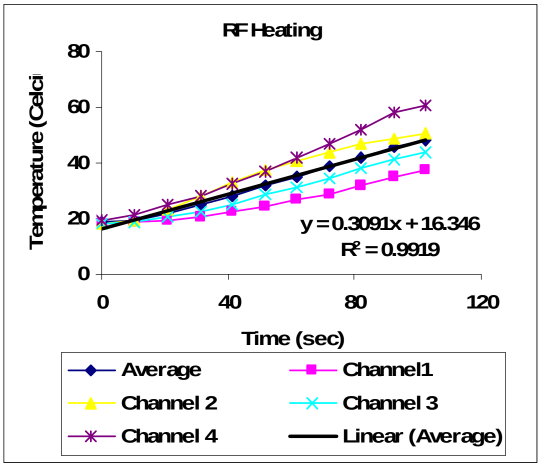

RF Heating
Temp. (Celcu
100
80
60
40
20
0
0
40
80
120
160
200
Time (Sec)
y = 0.2583x + 22.642
R^2 = 0.9973
Average
Channel 1
Channel 2
Channel 3
Channel 4
Linear (Average)

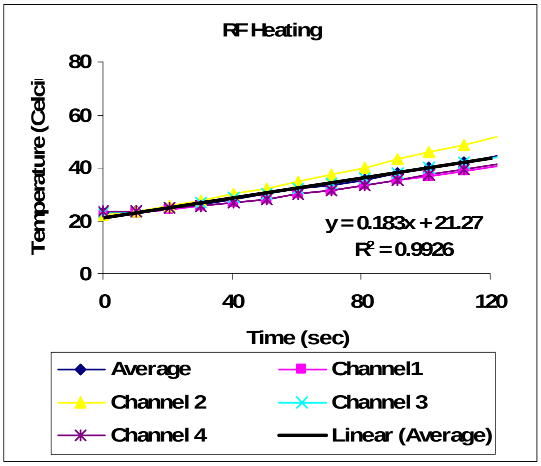

RF Heating
Temp. (Celcui
80
60
40
20
0
0
40
80
120
160
200
240
Time (Sec)
y = 0.1785x + 29.612
R^2 = 0.9977
Average
Channel 1
Channel 2
Channel 3
Channel 4
Linear (Average)

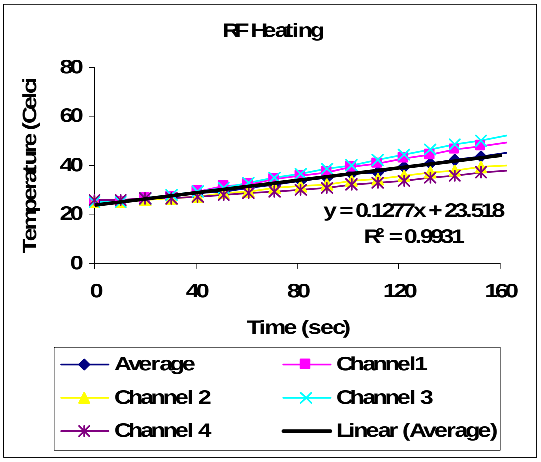

RF Heating
Temp. (Celcu
80
60
40
20
0
0
50
100
150
200
250
Time (Sec)
y = 0.1455x + 28.244
R^2 = 0.994
Average
Channel 1
Channel 2
Channel 3
Channel 4
Linear (Average)

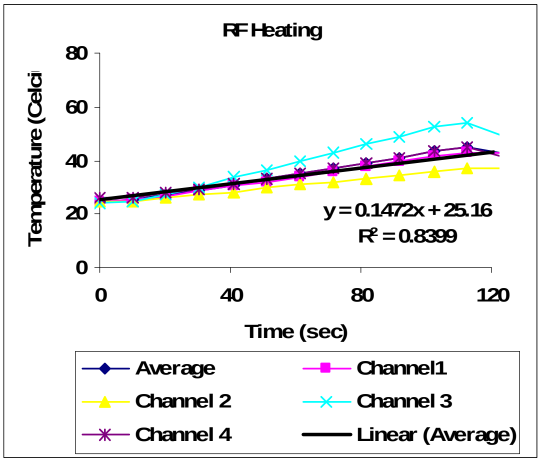

RF Heating
Temp. (Celcu
120
100
80
60
40
20
0
0
40
80
120
160
200
240
Time (Sec)
y = 0.203x + 35.374
R^2 = 0.9795
Average
Channel 1
Channel 2
Channel 3
Channel 4
Linear (Average)

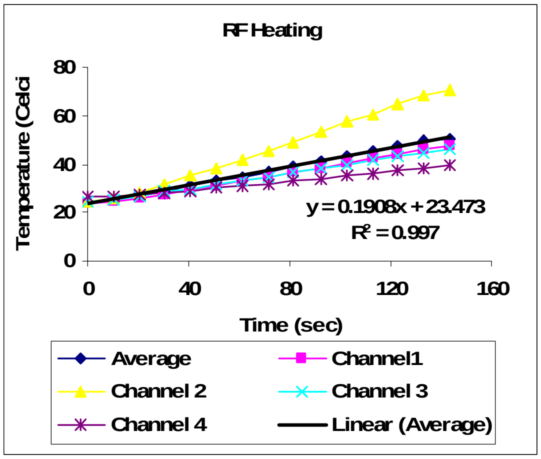

RF Heating
Temp. (Celcu
120
100
80
60
40
20
0
0
40
80
120
160
200
240
Time (Sec)
y = 0.173x + 27.899
R^2 = 0.9975
Average
Channel 1
Channel 2
Channel 3
Channel 4
Linear (Average)

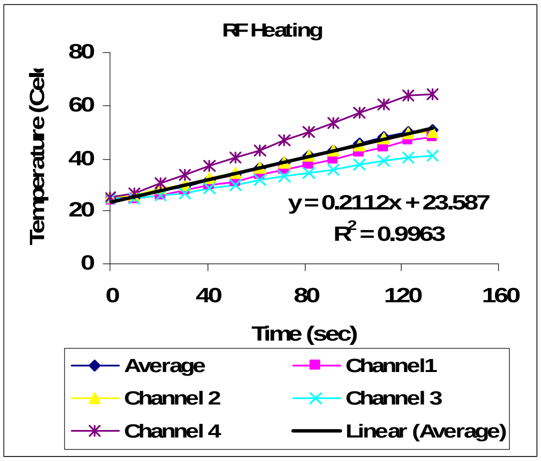

RF Heating
Temperature (Celci
80
60
40
20
0
0
40
80
120
Time (sec)
y = 0.3091x + 16.346
R² = 0.9919
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

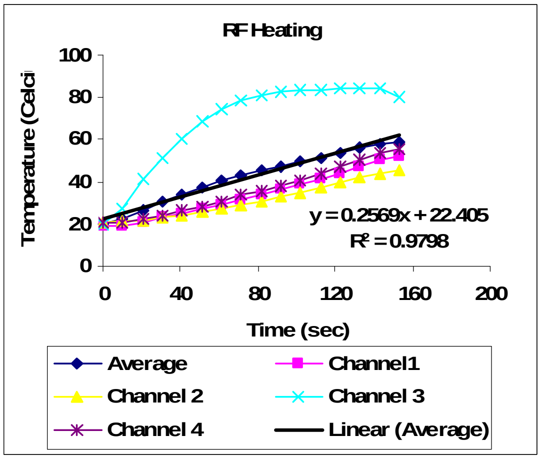

RF Heating
Temperature (Celci
80
60
40
20
0
0
40
80
120
Time (sec)
y = 0.183x + 21.27
R² = 0.9926
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

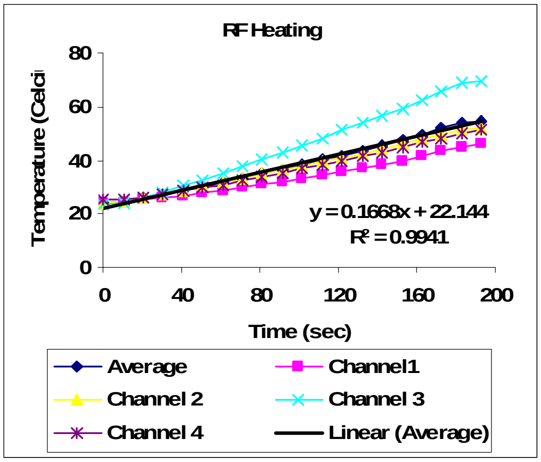

RF Heating
Temperature (Celci
80
60
40
20
0
0
40
80
120
160
Time (sec)
y = 0.1277x + 23.518
R² = 0.9931
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

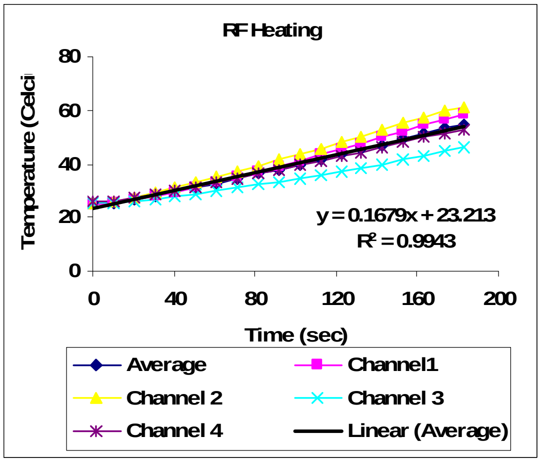

RF Heating
Temperature (Celci
80
60
40
20
0
0
40
80
120
Time (sec)
y = 0.1472x + 25.16
R² = 0.8399
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

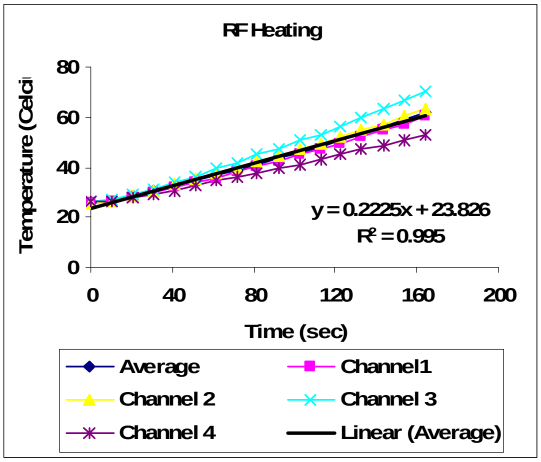

RF Heating
Temperature (Celci
80
60
40
20
0
0
40
80
120
160
Time (sec)
y = 0.1908x + 23.473
R² = 0.997
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

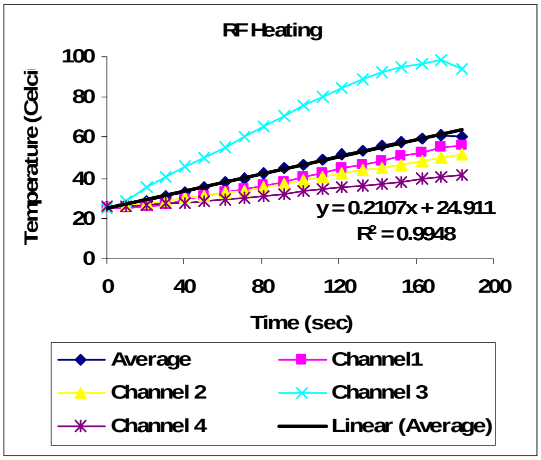

RF Heating
Temperature (Celc
80
60
40
20
0
0
40
80
120
160
Time (sec)
y = 0.2112x + 23.587
R² = 0.9963
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

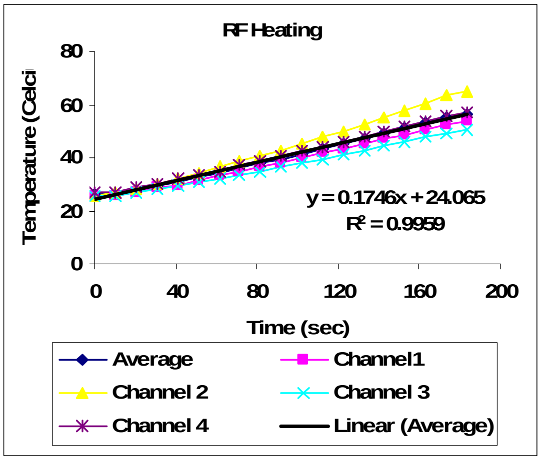

RF Heating
Temperature (Celci
100
80
60
40
20
0
0
40
80
120
160
200
Time (sec)
y = 0.2569x + 22.405
R² = 0.9798
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

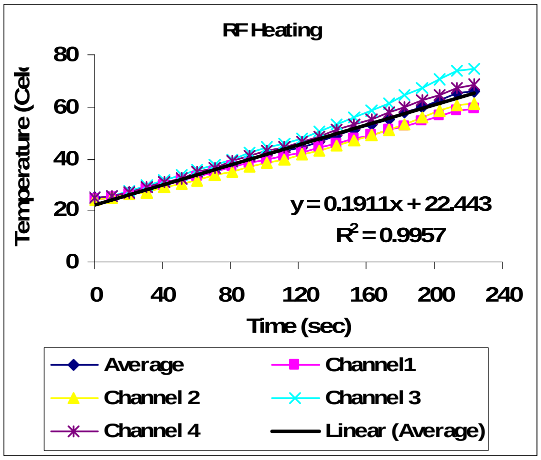

RF Heating
Temperature (Celci
80
60
40
20
0
0
40
80
120
160
200
Time (sec)
y = 0.1668x + 22.144
R² = 0.9941
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

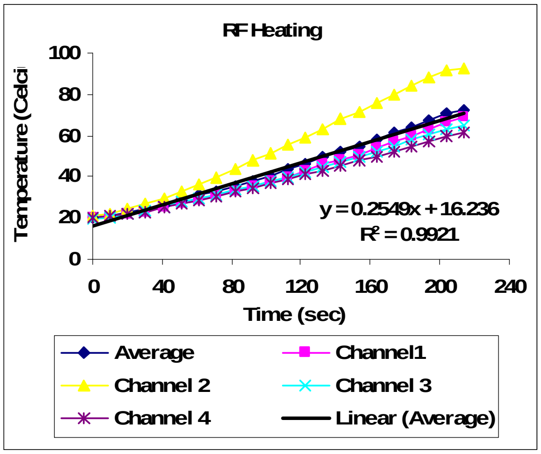

RF Heating
Temperature (Celci
80
60
40
20
0
0
40
80
120
160
200
Time (sec)
y = 0.1679x + 23.213
R² = 0.9943
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

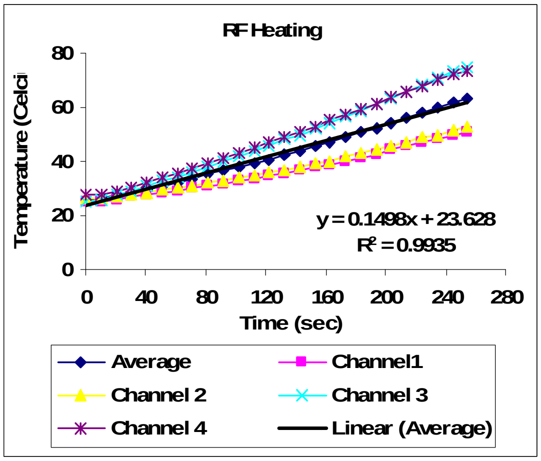

RF Heating
Temperature (Celci
80
60
40
20
0
0
40
80
120
160
200
Time (sec)
y = 0.2225x + 23.826
R² = 0.995
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

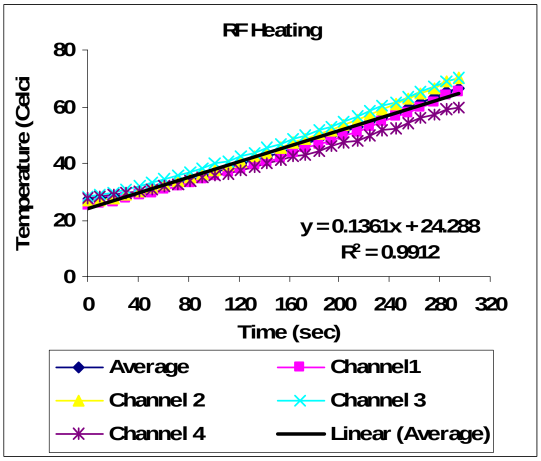

RF Heating
Temperature (Celci
100
80
60
40
20
0
0
40
80
120
160
200
Time (sec)
y = 0.2107x + 24.911
R² = 0.9948
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

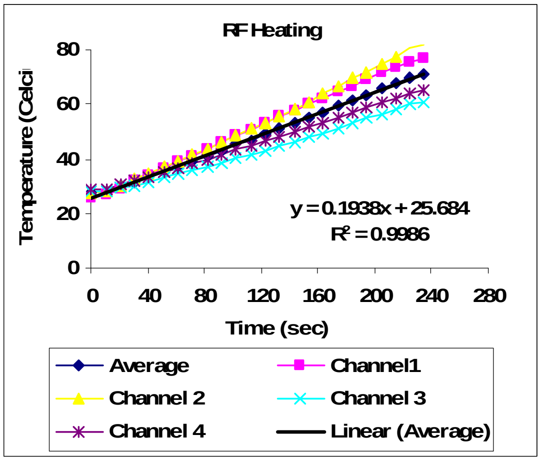

RF Heating
Temperature (Celci
80
60
40
20
0
0
40
80
120
160
200
Time (sec)
y = 0.1746x + 24.065
R² = 0.9959
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

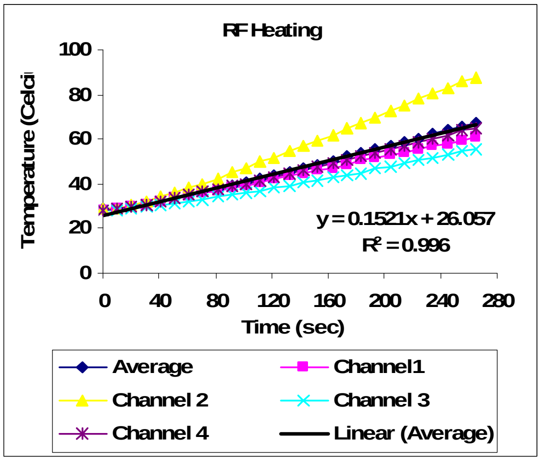

RF Heating
Temperature (Celc
80
60
40
20
0
0
40
80
120
160
200
240
Time (sec)
y = 0.1911x + 22.443
R² = 0.9957
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

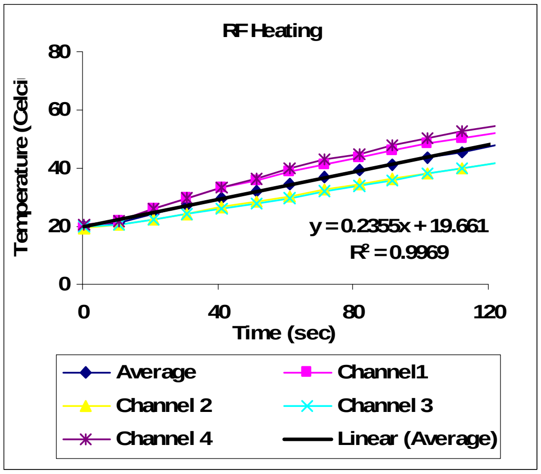

RF Heating
Temperature (Celci
100
80
60
40
20
0
0
40
80
120
160
200
240
Time (sec)
y = 0.2549x + 16.236
R² = 0.9921
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

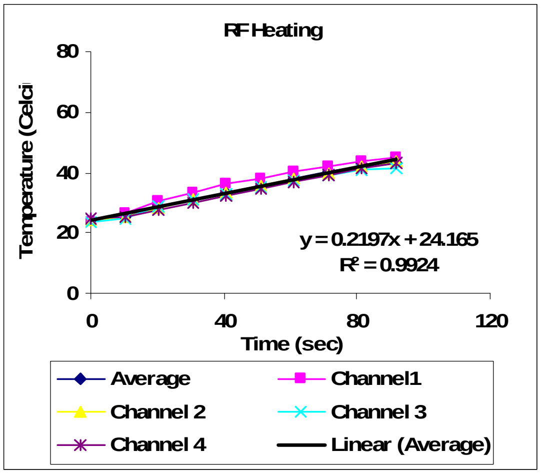

RF Heating
Temperature (Celci
80
60
40
20
0
0
40
80
120
160
200
240
280
Time (sec)
y = 0.1498x + 23.628
R² = 0.9935
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

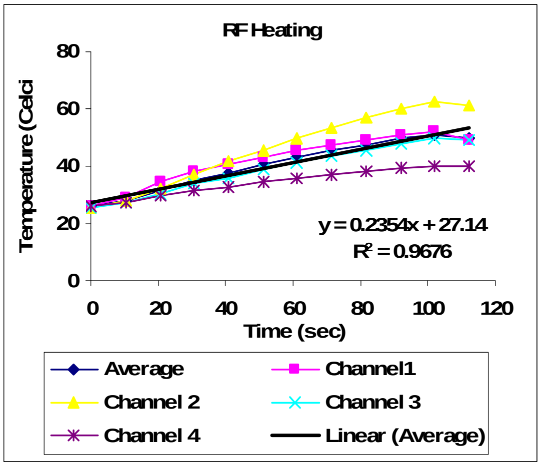

RF Heating
Temperature (Celci
80
60
40
20
0
0
40
80
120
160
200
240
280
320
Time (sec)
y = 0.1361x + 24.288
R² = 0.9912
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

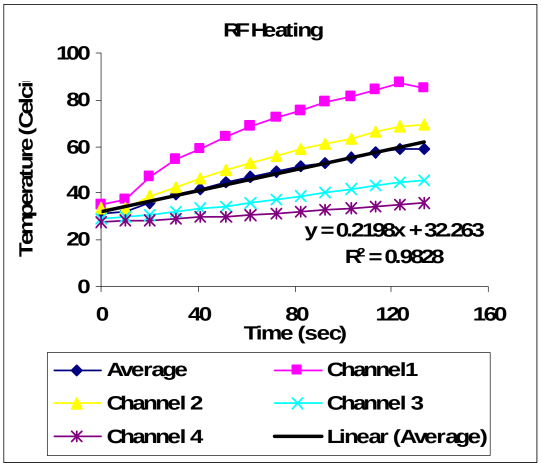

RF Heating
Temperature (Celci
80
60
40
20
0
0
40
80
120
160
200
240
280
Time (sec)
y = 0.1938x + 25.684
R² = 0.9986
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

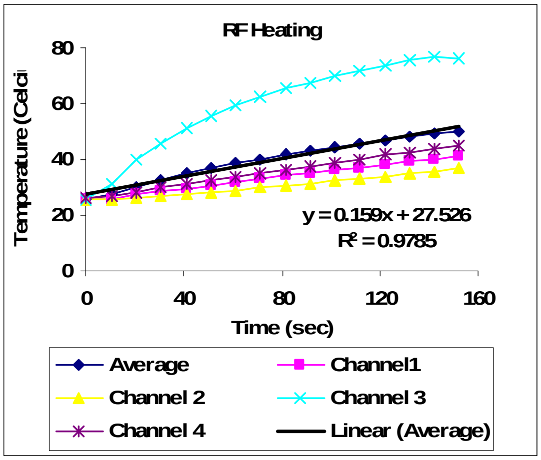

RF Heating
Temperature (Celci
100
80
60
40
20
0
0
40
80
120
160
200
240
280
Time (sec)
y = 0.1521x + 26.057
R² = 0.996
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

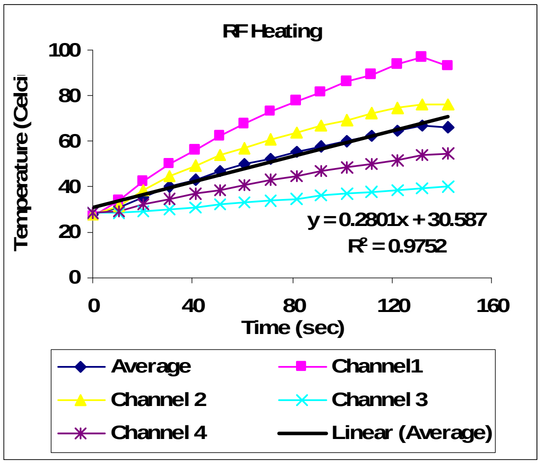

RF Heating
Temperature (Celci
80
60
40
20
0
0
40
80
120
Time (sec)
y = 0.2355x + 19.661
R² = 0.9969
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

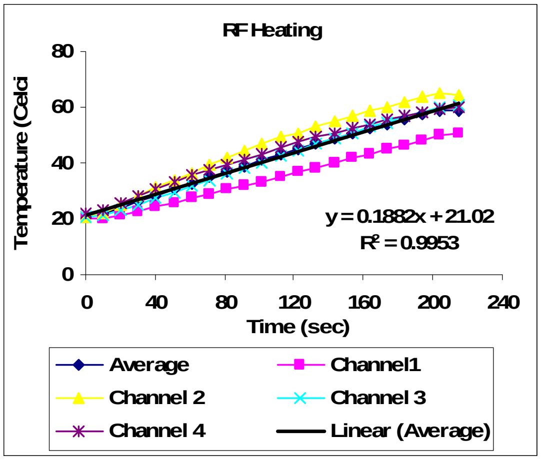

RF Heating
Temperature (Celci
80
60
40
20
0
0
40
80
120
Time (sec)
y = 0.2197x + 24.165
R² = 0.9924
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

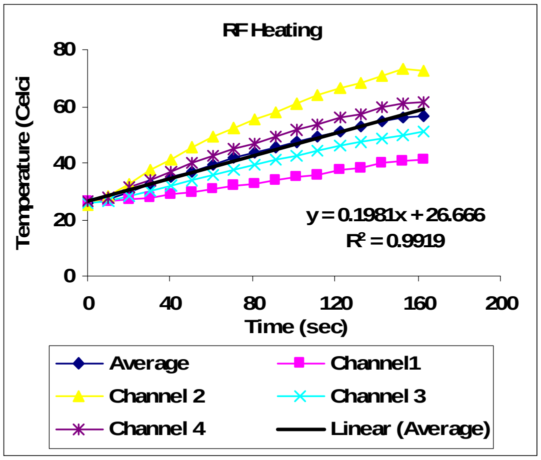

RF Heating
Temperature (Celci
80
60
40
20
0
0
20
40
60
80
100
120
Time (sec)
y = 0.2354x + 27.14
R² = 0.9676
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

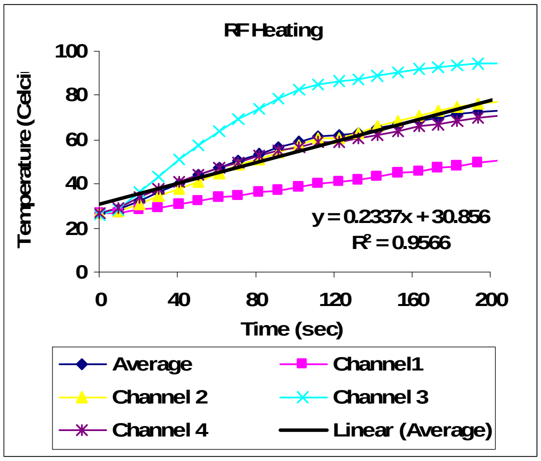

RF Heating
Temperature (Celci
100
80
60
40
20
0
0
40
80
120
160
Time (sec)
y = 0.2198x + 32.263
R² = 0.9828
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

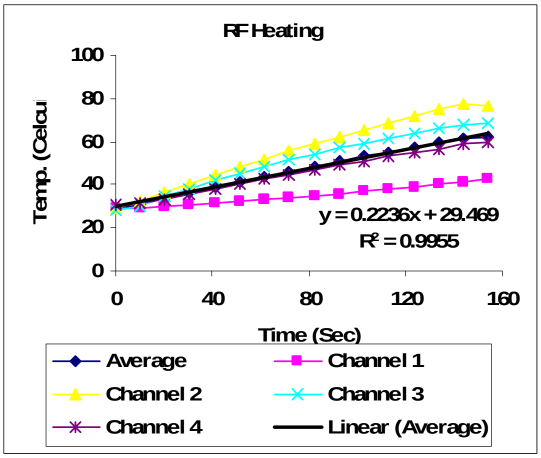

RF Heating
Temperature (Celci
80
60
40
20
0
0
40
80
120
160
Time (sec)
y = 0.159x + 27.526
R² = 0.9785
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

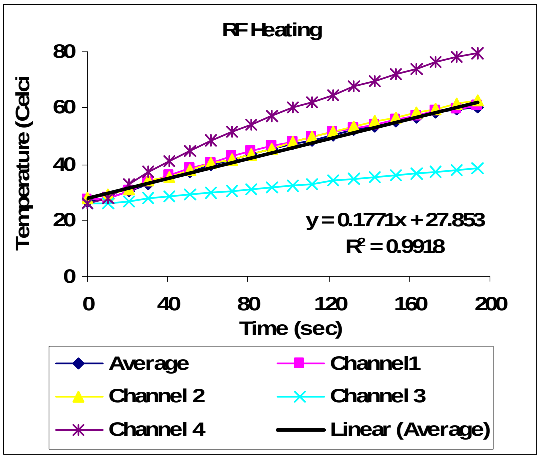

RF Heating
Temperature (Celci
100
80
60
40
20
0
0
40
80
120
160
Time (sec)
y = 0.2801x + 30.587
R² = 0.9752
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

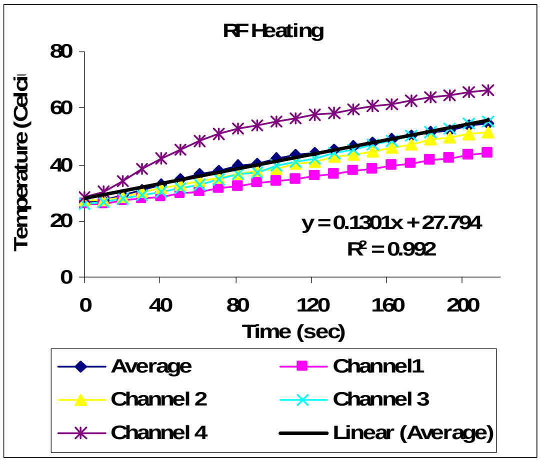

RF Heating
Temperature (Celci
80
60
40
20
0
0
40
80
120
160
200
240
Time (sec)
y = 0.1882x + 21.02
$R^2 = 0.9953$
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

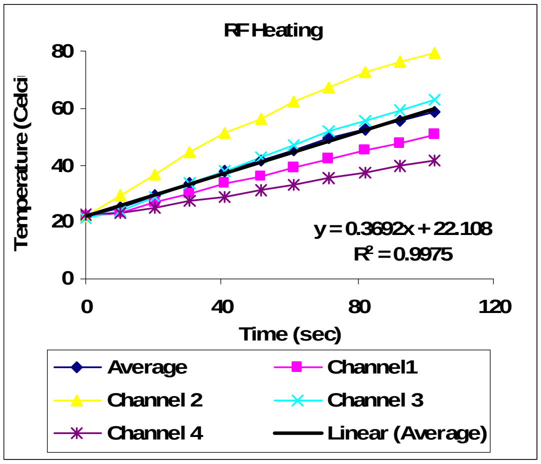

RF Heating
Temperature (Celci
80
60
40
20
0
0
40
80
120
160
200
Time (sec)
y = 0.1981x + 26.666
$R^2 = 0.9919$
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

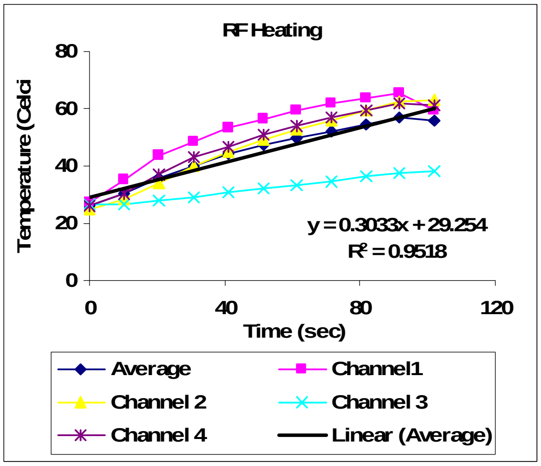

RF Heating
Temperature (Celci
100
80
60
40
20
0
0
40
80
120
160
200
Time (sec)
y = 0.2337x + 30.856
$R^2 = 0.9566$
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

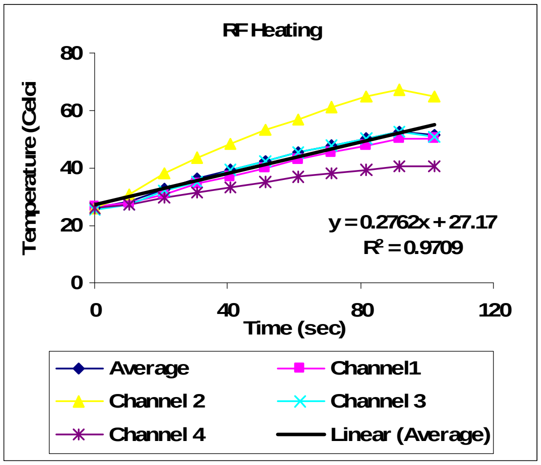

RF Heating
Temp. (Celcu
100
80
60
40
20
0
0
40
80
120
160
Time (Sec)
y = 0.2236x + 29.469
$R^2 = 0.9955$
Average
Channel 1
Channel 2
Channel 3
Channel 4
Linear (Average)

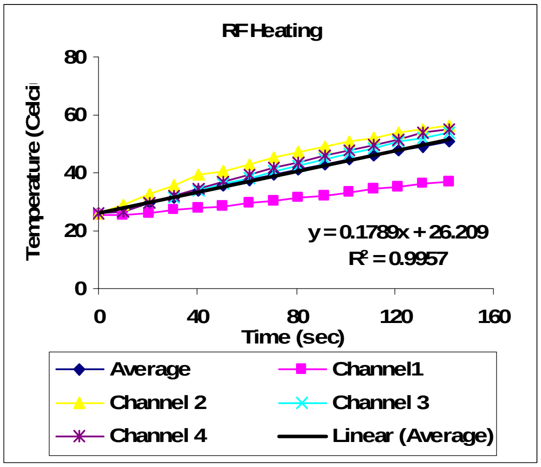

RF Heating
Temperature (Celci
80
60
40
20
0
0
40
80
120
160
200
Time (sec)
y = 0.1771x + 27.853
$R^2 = 0.9918$
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

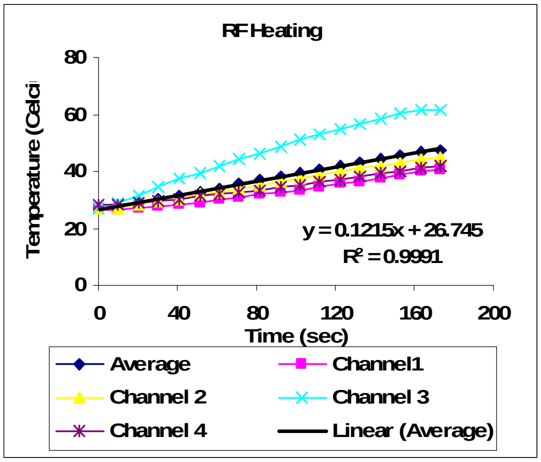

RF Heating
Temperature (Celci
80
60
40
20
0
0
40
80
120
160
200
Time (sec)
y = 0.1301x + 27.794
$R^2 = 0.992$
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

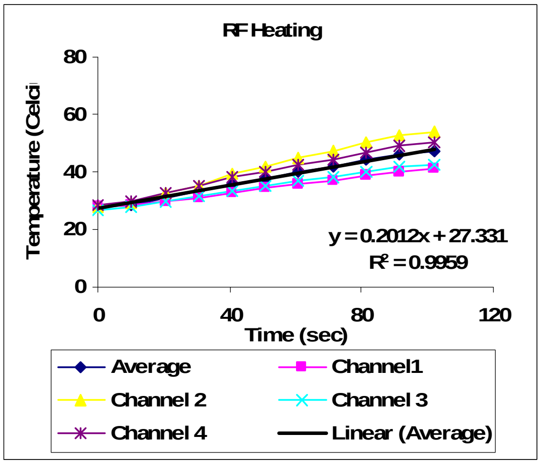

RF Heating
Temperature (Celci
Time (sec)
0
20
40
60
80
0
40
80
120
y = 0.3692x + 22.108
R^2 = 0.9975
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

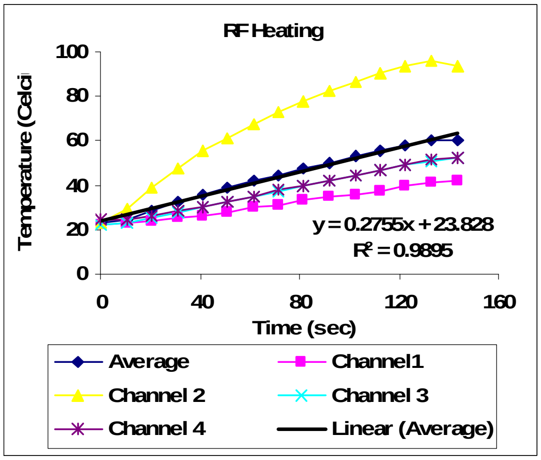

RF Heating
Temperature (Celci
Time (sec)
0
20
40
60
80
0
40
80
120
y = 0.3033x + 29.254
R^2 = 0.9518
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

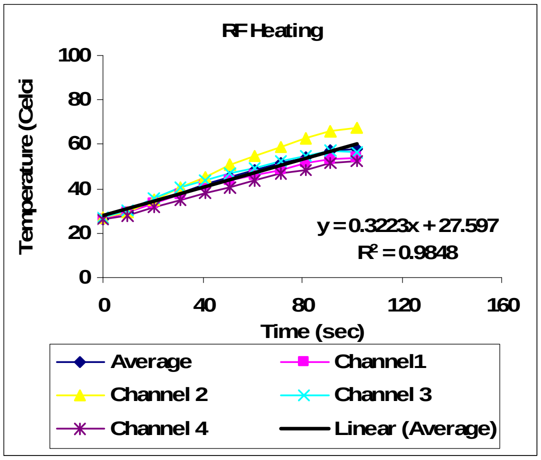

RF Heating
Temperature (Celci
Time (sec)
0
20
40
60
80
0
40
80
120
y = 0.2762x + 27.17
R^2 = 0.9709
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

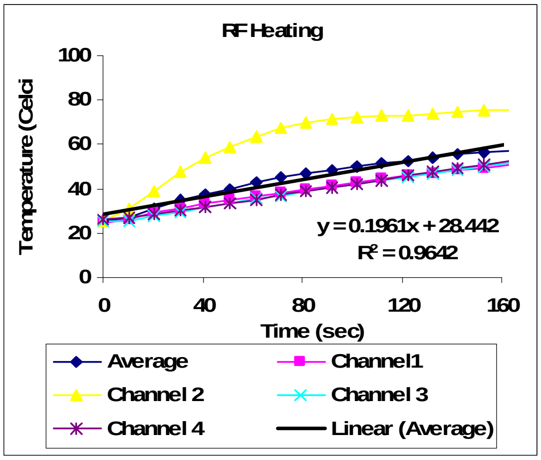

RF Heating
Temperature (Celci
Time (sec)
0
20
40
60
80
0
40
80
120
160
y = 0.1789x + 26.209
R^2 = 0.9957
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

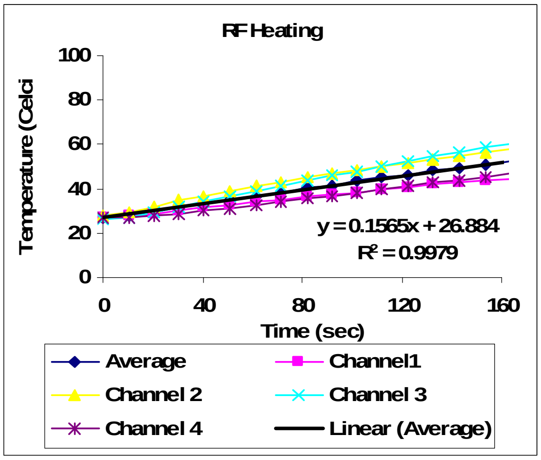

RF Heating
Temperature (Celci
Time (sec)
0
20
40
60
80
0
40
80
120
160
200
y = 0.1215x + 26.745
R^2 = 0.9991
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

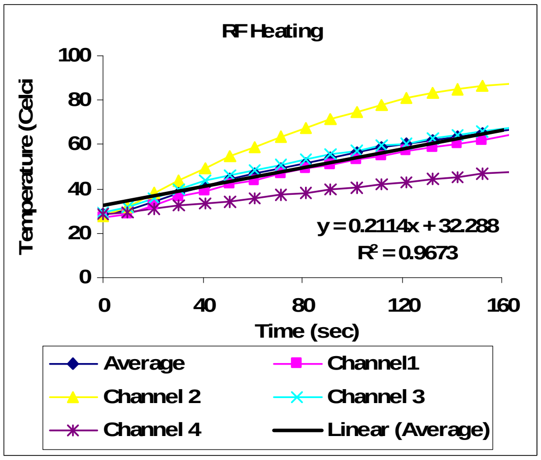

RF Heating
Temperature (Celci
Time (sec)
0
20
40
60
80
0
40
80
120
y = 0.2012x + 27.331
R^2 = 0.9959
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

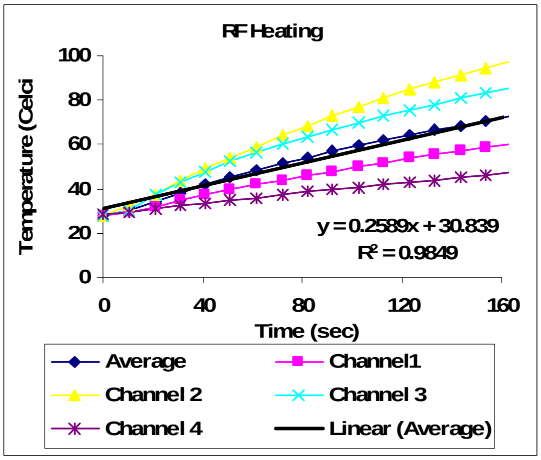

RF Heating
Temperature (Celci
Time (sec)
100
80
60
40
20
0
0
40
80
120
160
y = 0.2755x + 23.828
R² = 0.9895
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

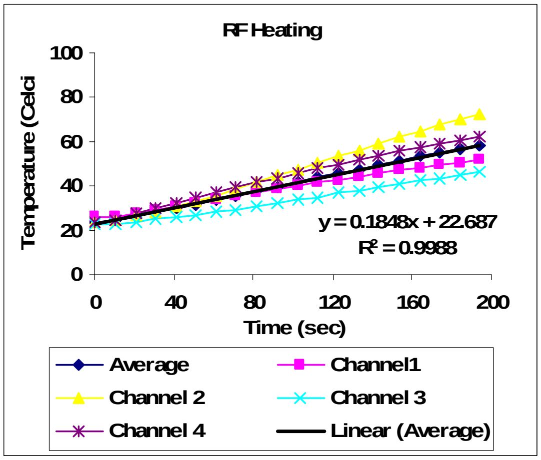

RF Heating
Temperature (Celci
Time (sec)
100
80
60
40
20
0
0
40
80
120
160
y = 0.3223x + 27.597
R² = 0.9848
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

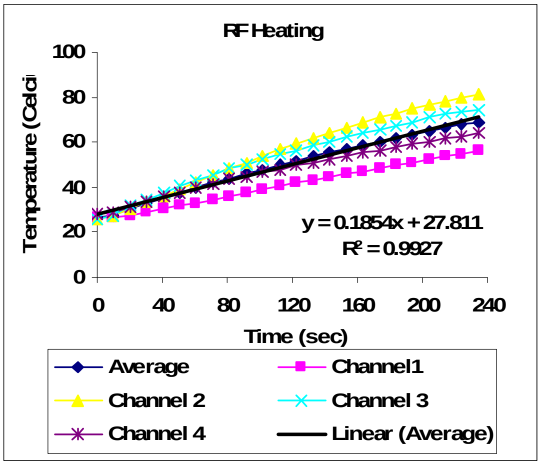

RF Heating
Temperature (Celci
Time (sec)
100
80
60
40
20
0
0
40
80
120
160
y = 0.1961x + 28.442
R² = 0.9642
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

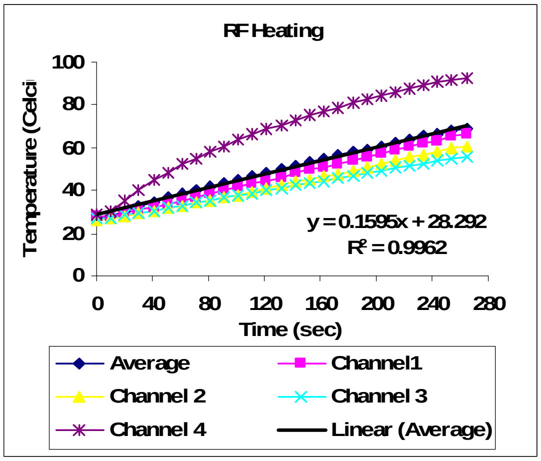

RF Heating
Temperature (Celci
Time (sec)
100
80
60
40
20
0
0
40
80
120
160
y = 0.1565x + 26.884
R² = 0.9979
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

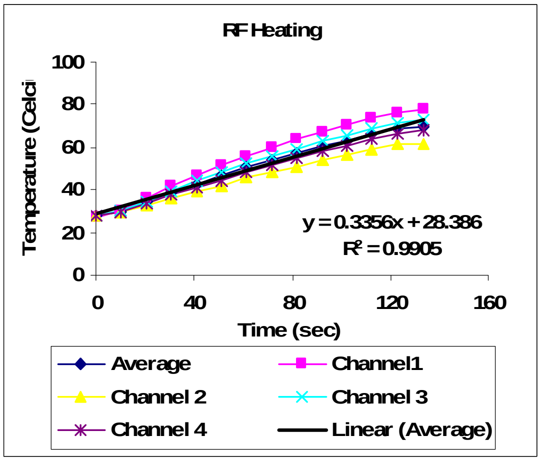

RF Heating
Temperature (Celci
Time (sec)
100
80
60
40
20
0
0
40
80
120
160
y = 0.2114x + 32.288
R² = 0.9673
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

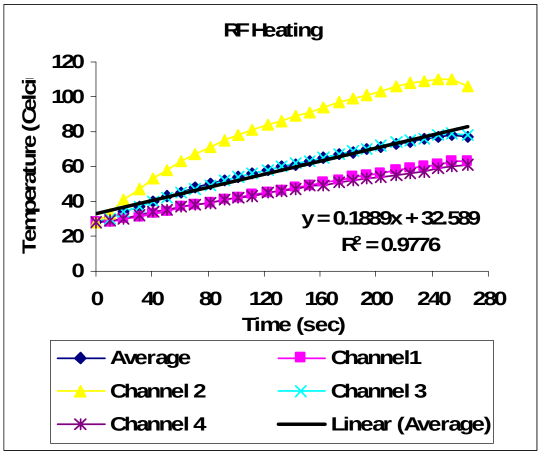

RF Heating
Temperature (Celci
Time (sec)
100
80
60
40
20
0
0
40
80
120
160
y = 0.2589x + 30.839
R² = 0.9849
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

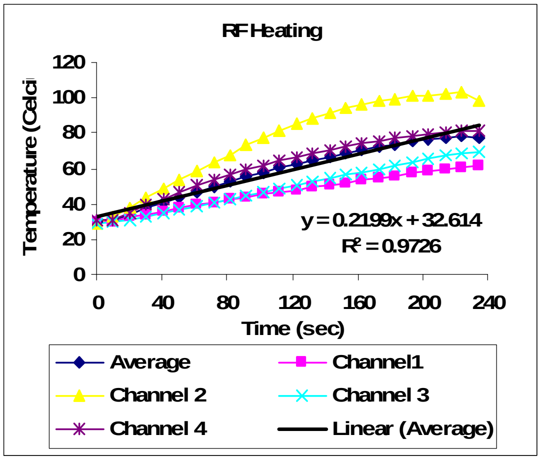

RF Heating
Temperature (Celci
Time (sec)
100
80
60
40
20
0
0
40
80
120
160
200
y = 0.1848x + 22.687
R^2 = 0.9988
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

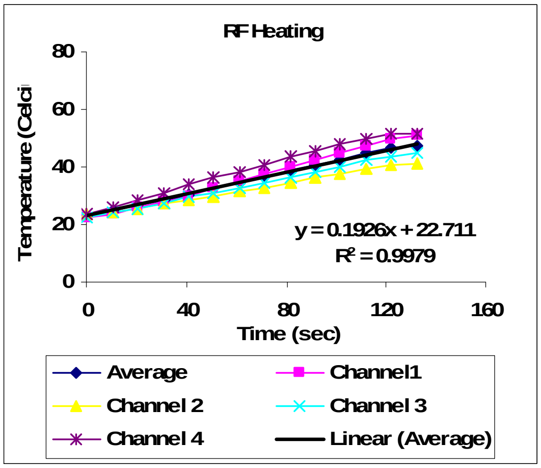

RF Heating
Temperature (Celci
Time (sec)
100
80
60
40
20
0
0
40
80
120
160
200
240
y = 0.1854x + 27.811
R^2 = 0.9927
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

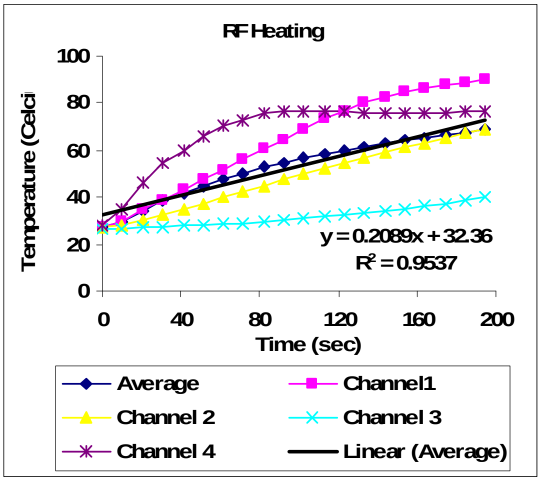

RF Heating
Temperature (Celci
Time (sec)
100
80
60
40
20
0
0
40
80
120
160
200
240
280
y = 0.1595x + 28.292
R^2 = 0.9962
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

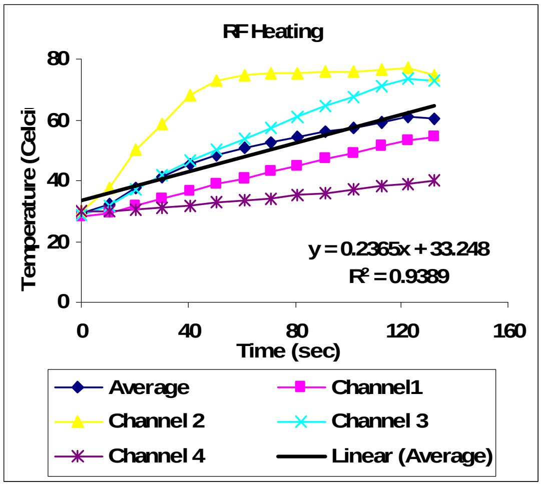

RF Heating
Temperature (Celci
Time (sec)
100
80
60
40
20
0
0
40
80
120
160
y = 0.3356x + 28.386
R^2 = 0.9905
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

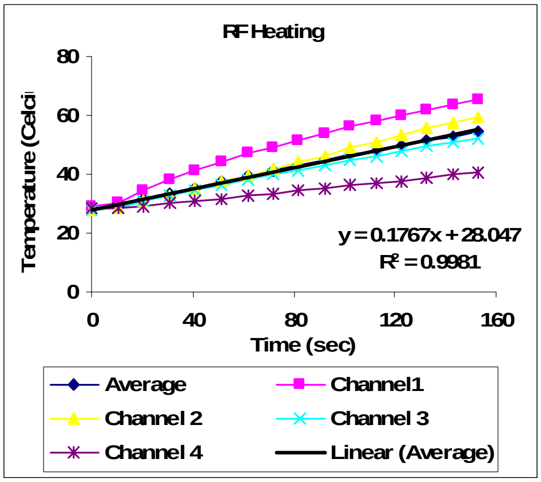

RF Heating
Temperature (Celci
Time (sec)
120
100
80
60
40
20
0
0
40
80
120
160
200
240
280
y = 0.1889x + 32.589
R^2 = 0.9776
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

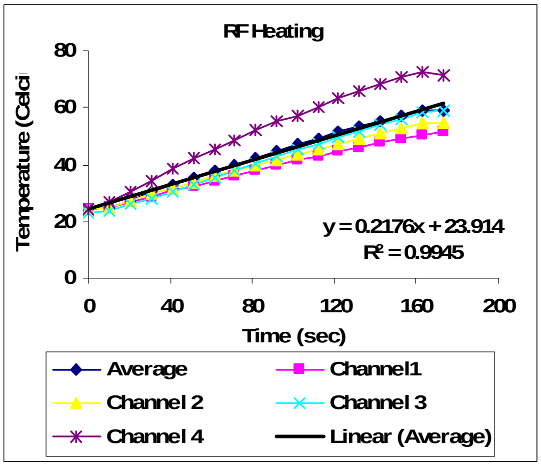

RF Heating
Temperature (Celci
Time (sec)
120
100
80
60
40
20
0
0
40
80
120
160
200
240
y = 0.2199x + 32.614
R^2 = 0.9726
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

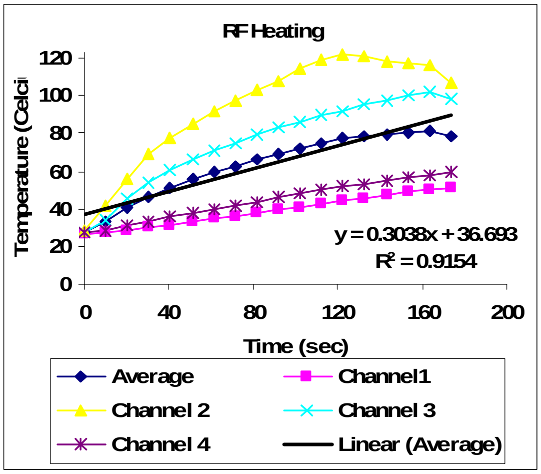

RF Heating
Temperature (Celci
Time (sec)
0
20
40
60
80
0
40
80
120
160
y = 0.1926x + 22.711
R^2 = 0.9979
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

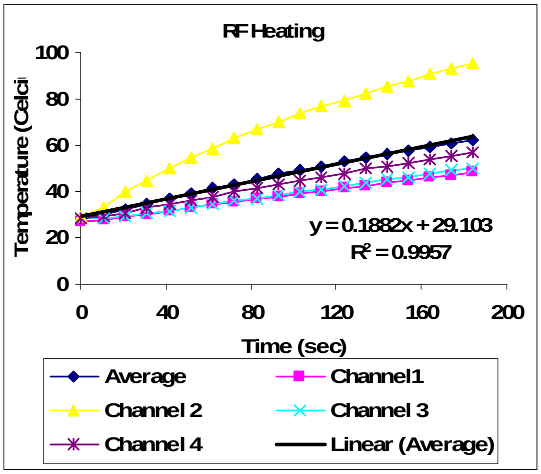

RF Heating
Temperature (Celci
Time (sec)
0
20
40
60
80
100
0
40
80
120
160
200
y = 0.2089x + 32.36
R^2 = 0.9537
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

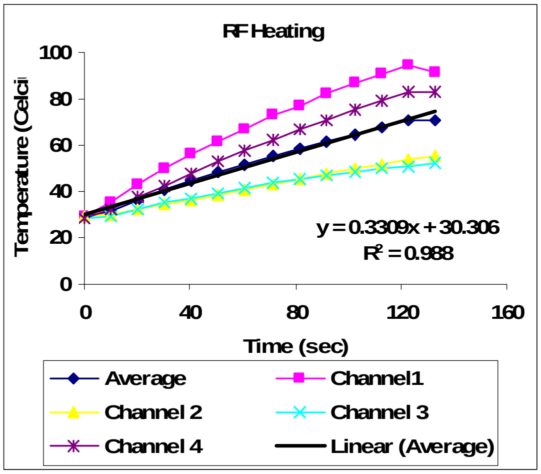

RF Heating
Temperature (Celci
Time (sec)
0
20
40
60
80
0
40
80
120
160
y = 0.2365x + 33.248
R^2 = 0.9389
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

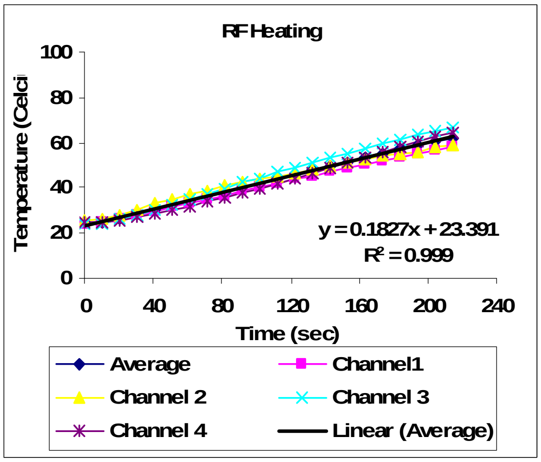

RF Heating
Temperature (Celci
Time (sec)
0
20
40
60
80
0
40
80
120
160
y = 0.1767x + 28.047
R^2 = 0.9981
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

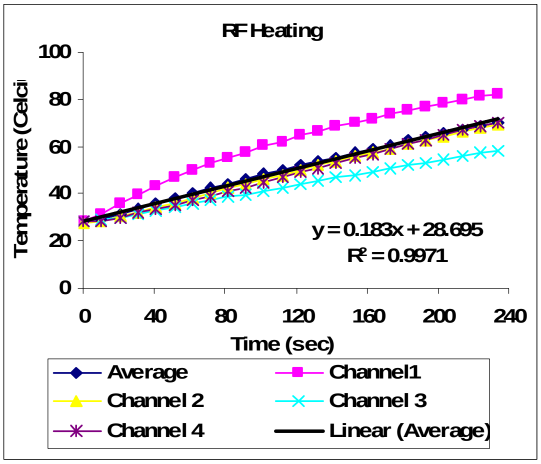

RF Heating
Temperature (Celci
80
60
40
20
0
0
40
80
120
160
200
Time (sec)
y = 0.2176x + 23.914
R² = 0.9945
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

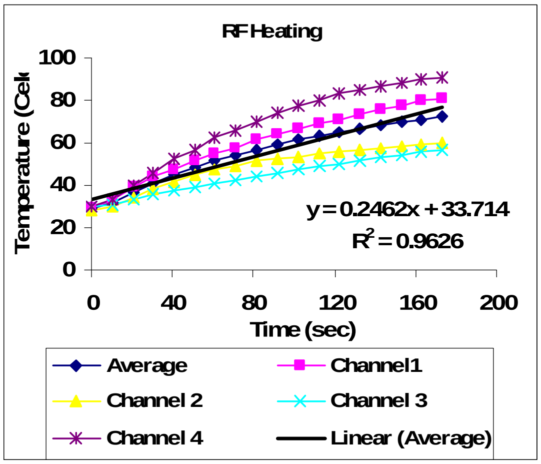

RF Heating
Temperature (Celci
120
100
80
60
40
20
0
0
40
80
120
160
200
Time (sec)
y = 0.3038x + 36.693
R² = 0.9154
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

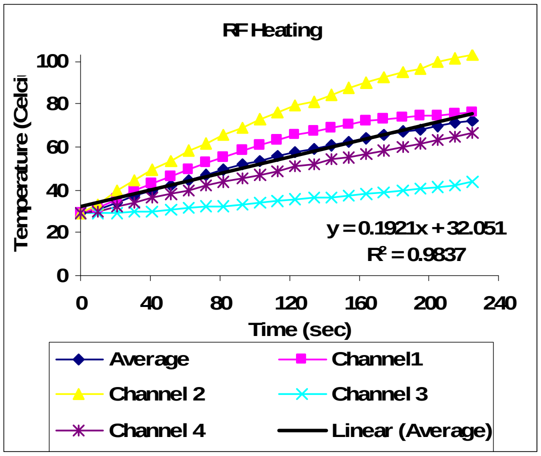

RF Heating
Temperature (Celci
100
80
60
40
20
0
0
40
80
120
160
200
Time (sec)
y = 0.1882x + 29.103
R² = 0.9957
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

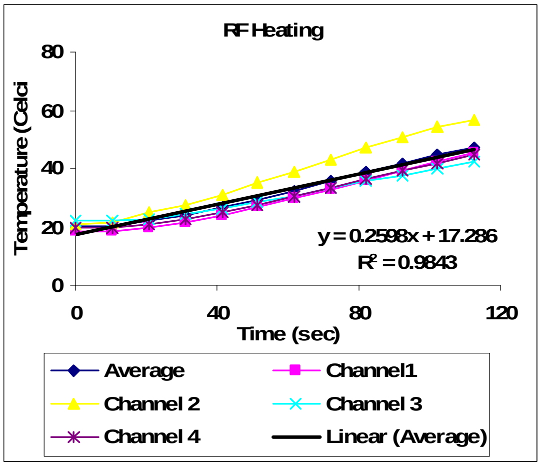

RF Heating
Temperature (Celci
100
80
60
40
20
0
0
40
80
120
160
Time (sec)
y = 0.3309x + 30.306
R² = 0.988
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

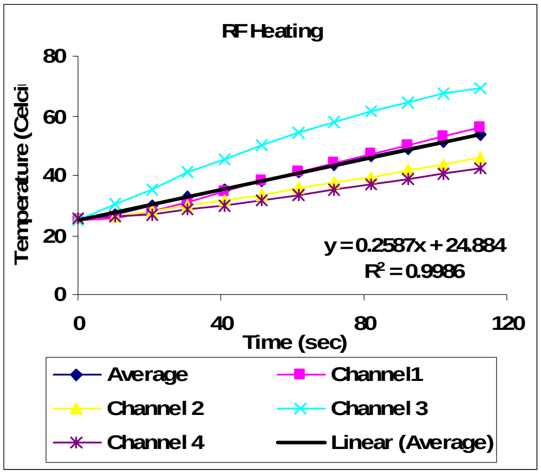

RF Heating
Temperature (Celci
100
80
60
40
20
0
0
40
80
120
160
200
240
Time (sec)
y = 0.1827x + 23.391
R² = 0.999
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

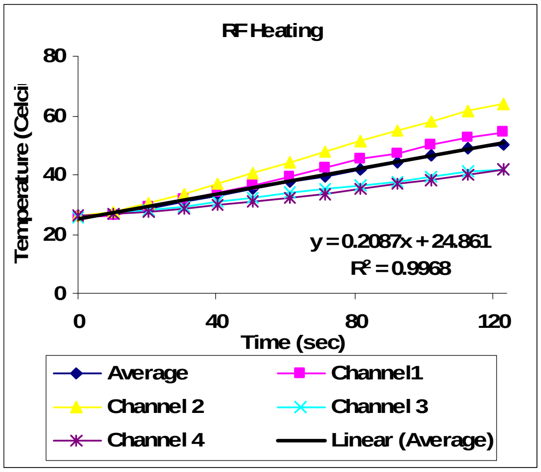

RF Heating
Temperature (Celci
100
80
60
40
20
0
0
40
80
120
160
200
240
Time (sec)
y = 0.183x + 28.695
R² = 0.9971
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

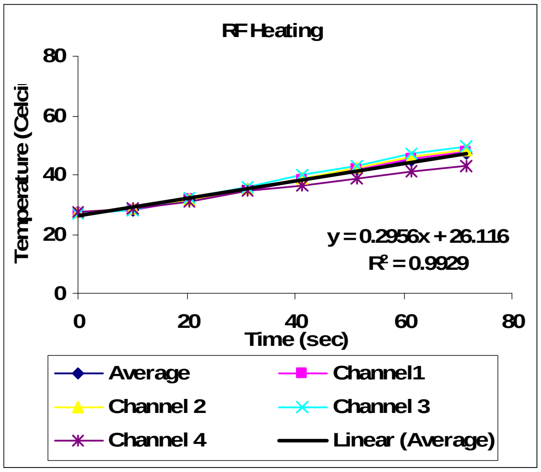

RF Heating
Temperature (Cel
100
80
60
40
20
0
0
40
80
120
160
200
Time (sec)
y = 0.2462x + 33.714
R² = 0.9626
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

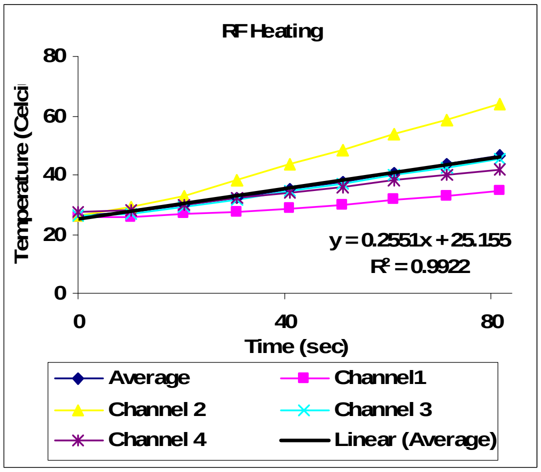

RF Heating
Temperature (Celci
100
80
60
40
20
0
0
40
80
120
160
200
240
Time (sec)
y = 0.1921x + 32.051
R² = 0.9837
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

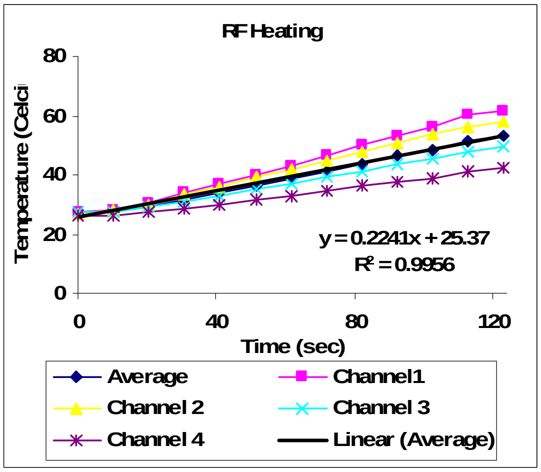

RF Heating
Temperature (Celci
80
60
40
20
0
0
40
80
120
Time (sec)
y = 0.2598x + 17.286
R² = 0.9843
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

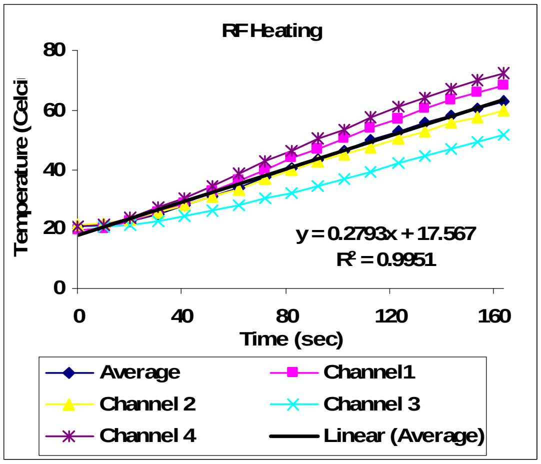

RF Heating
Temperature (Celci
80
60
40
20
0
0
40
80
120
Time (sec)
y = 0.2587x + 24.884
R² = 0.9986
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

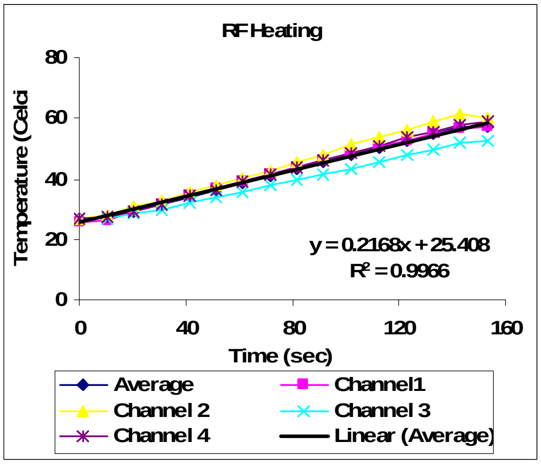

RF Heating
Temperature (Celci
80
60
40
20
0
0
40
80
120
Time (sec)
y = 0.2087x + 24.861
R² = 0.9968
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

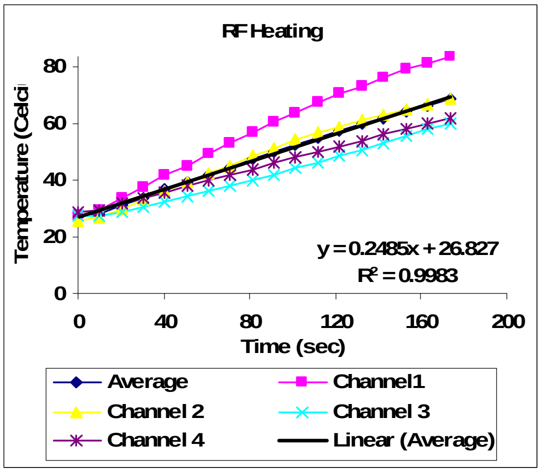

RF Heating
Temperature (Celci
80
60
40
20
0
0
20
40
60
80
Time (sec)
y = 0.2956x + 26.116
R² = 0.9929
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

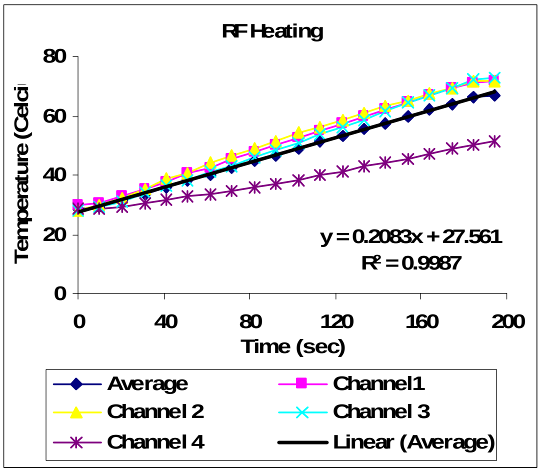

RF Heating
Temperature (Celci
80
60
40
20
0
0
40
80
Time (sec)
y = 0.2551x + 25.155
R² = 0.9922
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

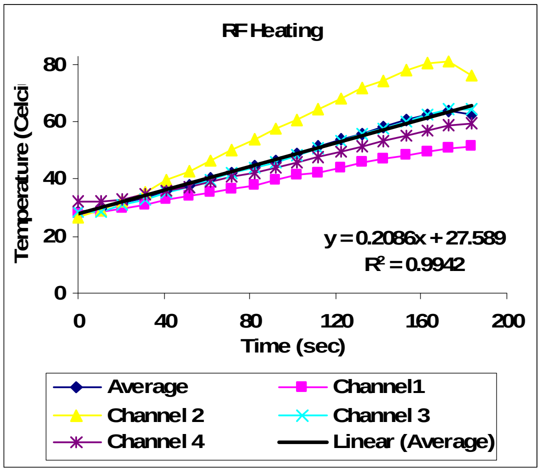

RF Heating
Temperature (Celci
80
60
40
20
0
0
40
80
120
Time (sec)
y = 0.2241x + 25.37
R² = 0.9956
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

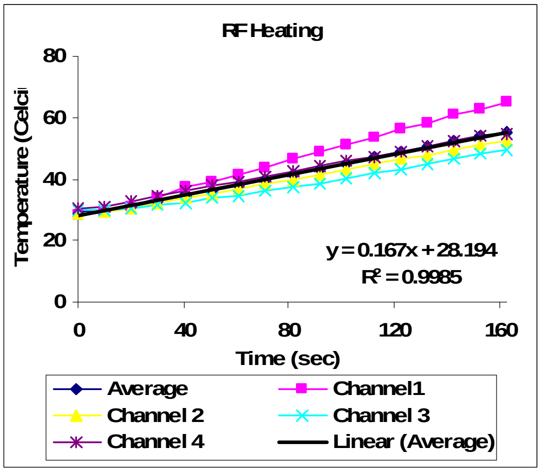

RF Heating
Temperature (Celci
80
60
40
20
0
0
40
80
120
160
Time (sec)
y = 0.2793x + 17.567
R² = 0.9951
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

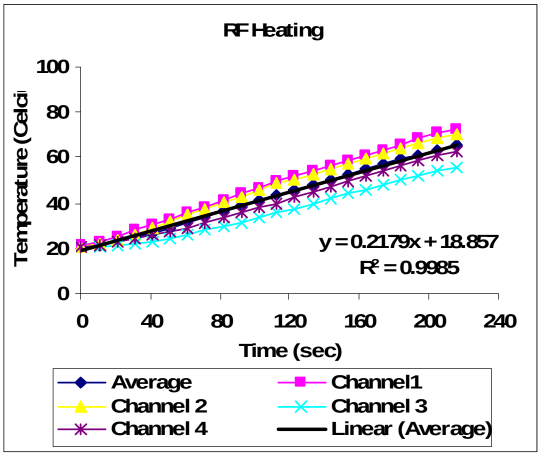

RF Heating
Temperature (Celci
80
60
40
20
0
0
40
80
120
160
Time (sec)
y = 0.2168x + 25.408
R² = 0.9966
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

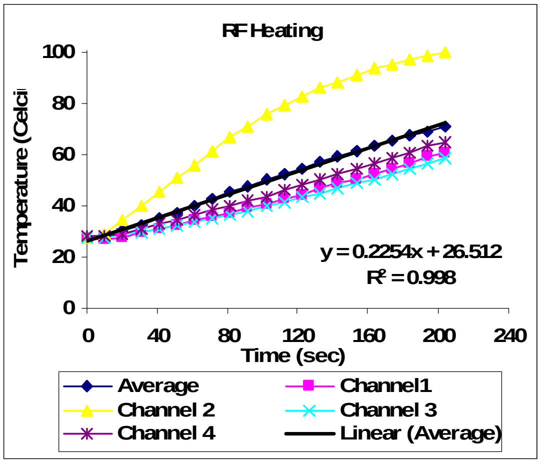

RF Heating
Temperature (Celci
80
60
40
20
0
0
40
80
120
160
200
Time (sec)
y = 0.2485x + 26.827
R² = 0.9983
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

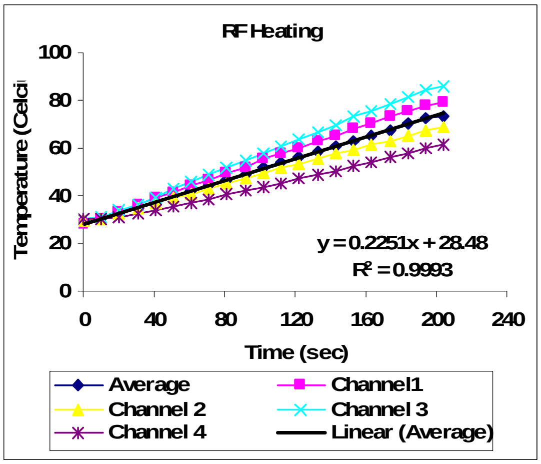

RF Heating
Temperature (Celci
80
60
40
20
0
0
40
80
120
160
200
Time (sec)
y = 0.2083x + 27.561
R² = 0.9987
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

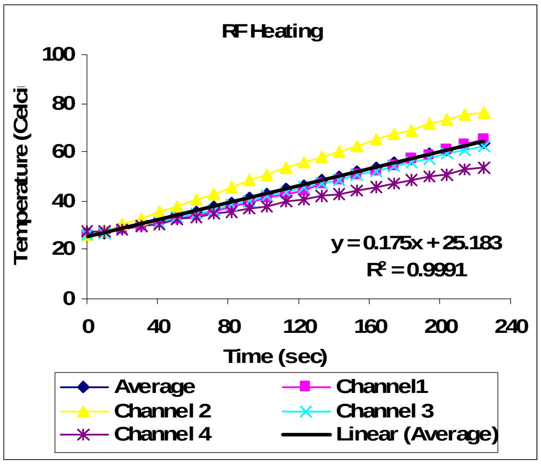

RF Heating
Temperature (Celci
80
60
40
20
0
0
40
80
120
160
200
Time (sec)
y = 0.2086x + 27.589
R² = 0.9942
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

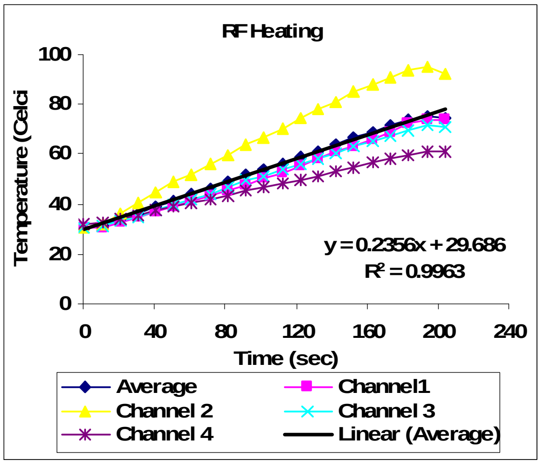

RF Heating
Temperature (Celci
80
60
40
20
0
0
40
80
120
160
Time (sec)
y = 0.167x + 28.194
R² = 0.9985
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

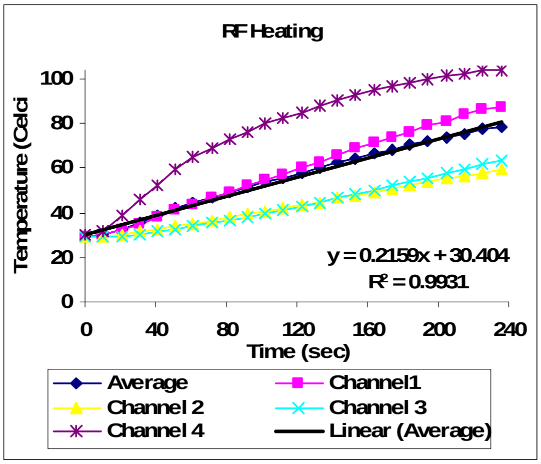

RF Heating
Temperature (Celci
100
80
60
40
20
0
0
40
80
120
160
200
240
Time (sec)
y = 0.2179x + 18.857
R² = 0.9985
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

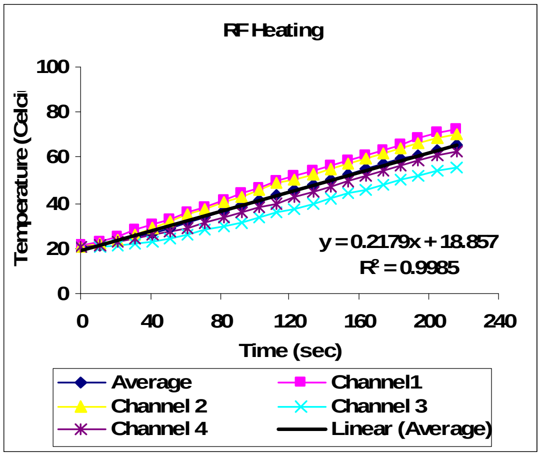

RF Heating
Temperature (Celci
100
80
60
40
20
0
0
40
80
120
160
200
240
Time (sec)
y = 0.2254x + 26.512
R² = 0.998
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

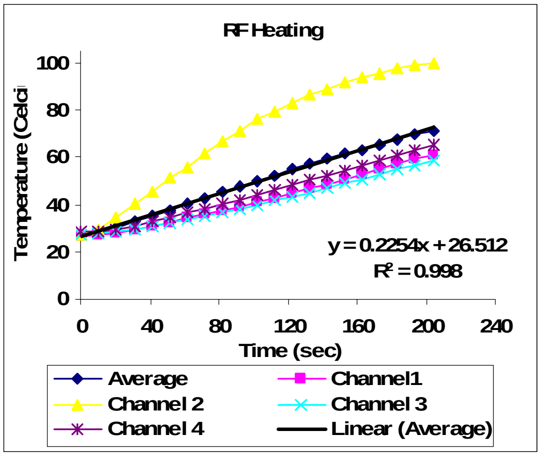

RF Heating
Temperature (Celci
100
80
60
40
20
0
0
40
80
120
160
200
240
Time (sec)
y = 0.2251x + 28.48
R² = 0.9993
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

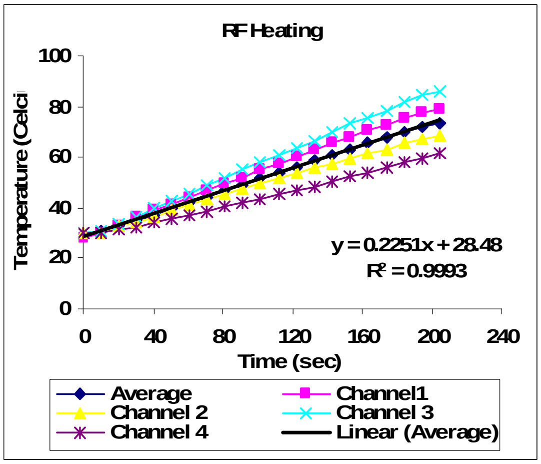

RF Heating
Temperature (Celci
100
80
60
40
20
0
0
40
80
120
160
200
240
Time (sec)
y = 0.175x + 25.183
R² = 0.9991
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

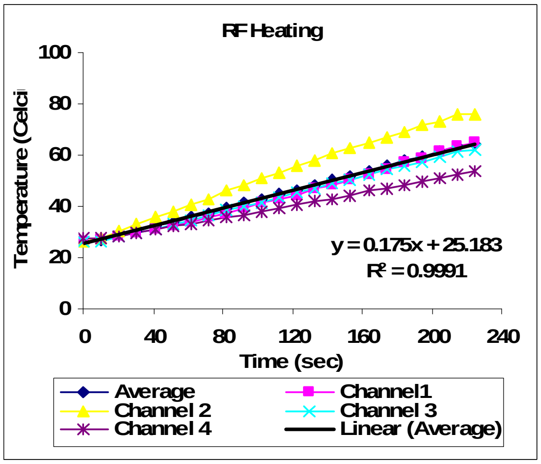

RF Heating
Temperature (Celci
100
80
60
40
20
0
0
40
80
120
160
200
240
Time (sec)
y = 0.2356x + 29.686
R² = 0.9963
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

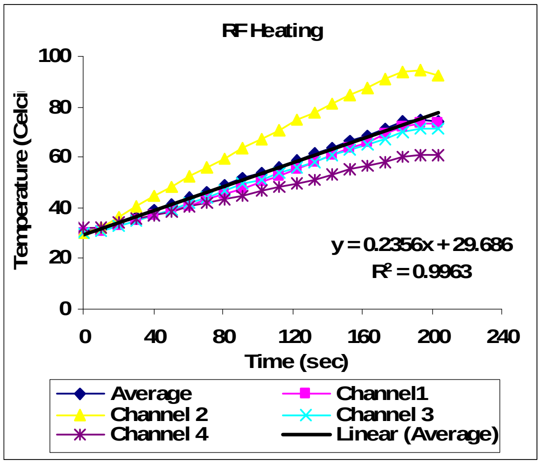

RF Heating
Temperature (Celci
100
80
60
40
20
0
0
40
80
120
160
200
240
Time (sec)
y = 0.2159x + 30.404
R² = 0.9931
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

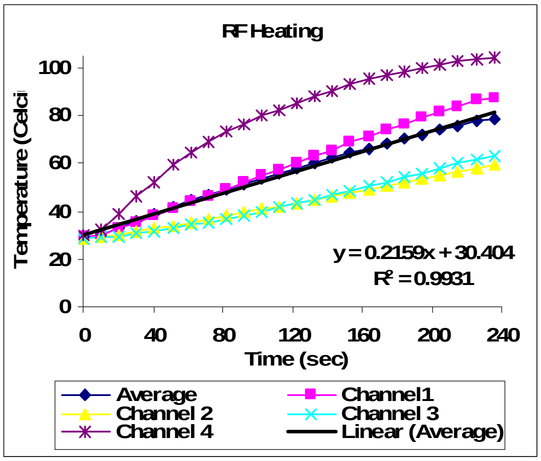

RF Heating
Temperature (Celci
100
80
60
40
20
0
0
40
80
120
160
200
240
Time (sec)
y = 0.2179x + 18.857
R^2 = 0.9985
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

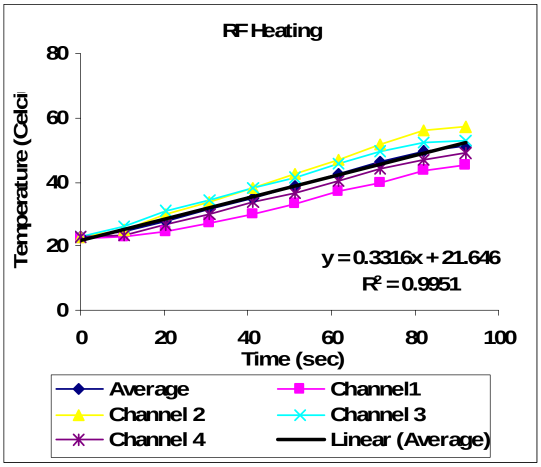

RF Heating
Temperature (Celci
100
80
60
40
20
0
0
40
80
120
160
200
240
Time (sec)
y = 0.2254x + 26.512
R^2 = 0.998
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

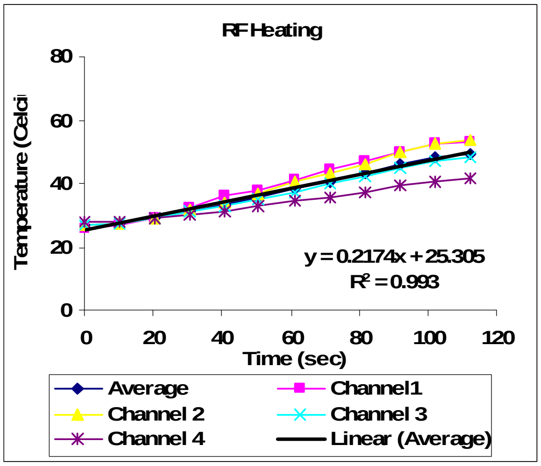

RF Heating
Temperature (Celci
100
80
60
40
20
0
0
40
80
120
160
200
240
Time (sec)
y = 0.2251x + 28.48
R^2 = 0.9993
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

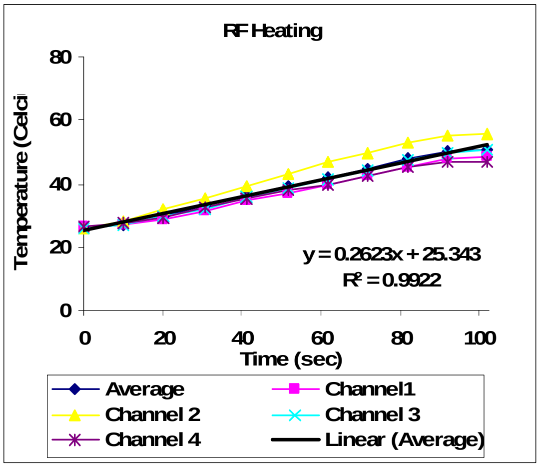

RF Heating
Temperature (Celci
100
80
60
40
20
0
0
40
80
120
160
200
240
Time (sec)
y = 0.175x + 25.183
R^2 = 0.9991
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

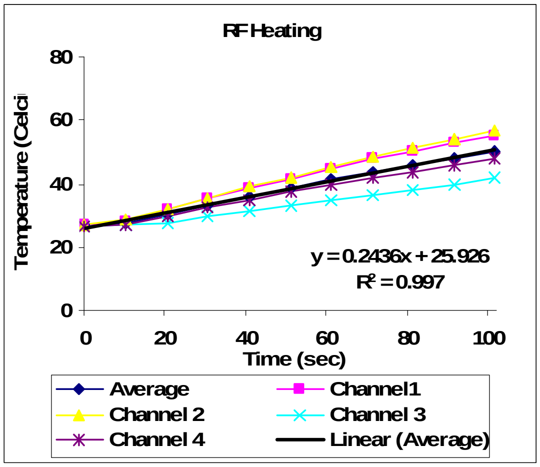

RF Heating
Temperature (Celci
100
80
60
40
20
0
0
40
80
120
160
200
240
Time (sec)
y = 0.2356x + 29.686
R^2 = 0.9963
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

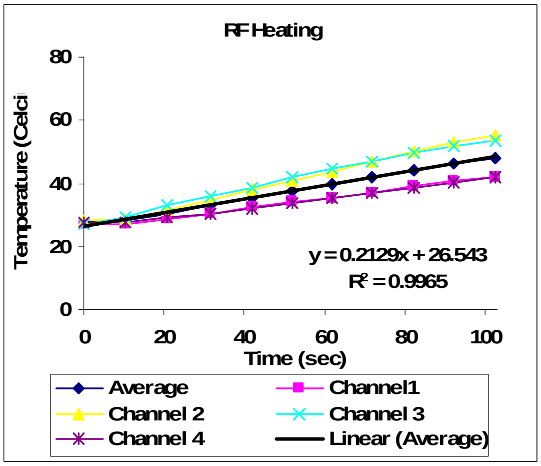

RF Heating
Temperature (Celci
100
80
60
40
20
0
0
40
80
120
160
200
240
Time (sec)
y = 0.2159x + 30.404
R^2 = 0.9931
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

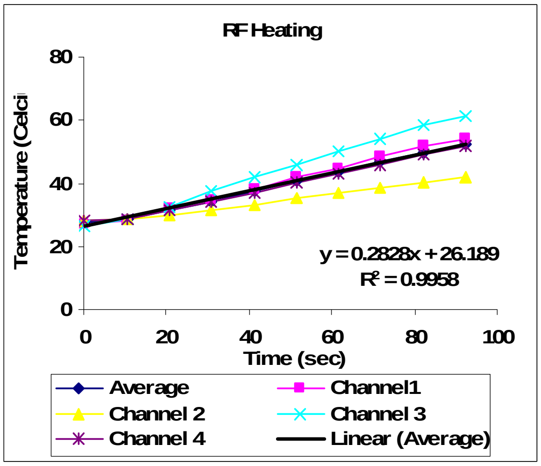

RF Heating
Temperature (Celci
Time (sec)
0
20
40
60
80
0
20
40
60
80
100
y = 0.3316x + 21.646
R^2 = 0.9951
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

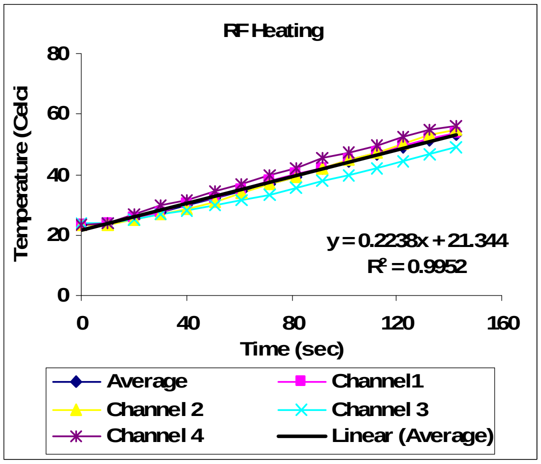

RF Heating
Temperature (Celci
Time (sec)
0
20
40
60
80
0
20
40
60
80
100
120
y = 0.2174x + 25.305
R^2 = 0.993
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

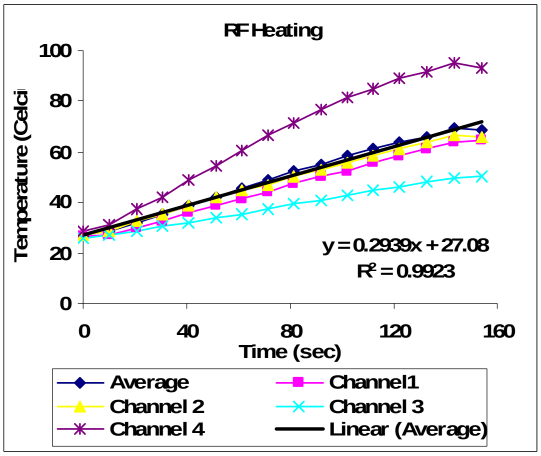

RF Heating
Temperature (Celci
Time (sec)
0
20
40
60
80
0
20
40
60
80
100
y = 0.2623x + 25.343
R^2 = 0.9922
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

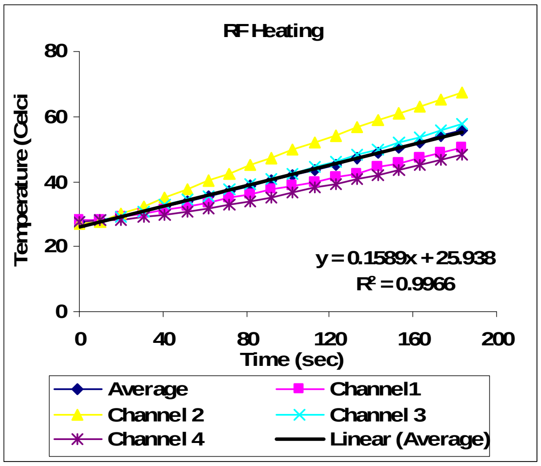

RF Heating
Temperature (Celci
Time (sec)
0
20
40
60
80
0
20
40
60
80
100
y = 0.2436x + 25.926
R^2 = 0.997
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

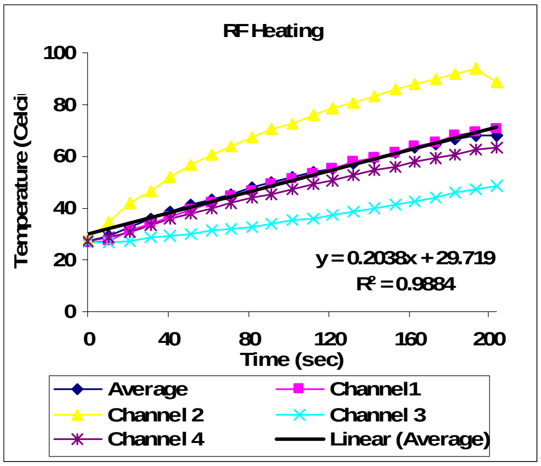

RF Heating
Temperature (Celci
Time (sec)
0
20
40
60
80
0
20
40
60
80
100
y = 0.2129x + 26.543
R^2 = 0.9965
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

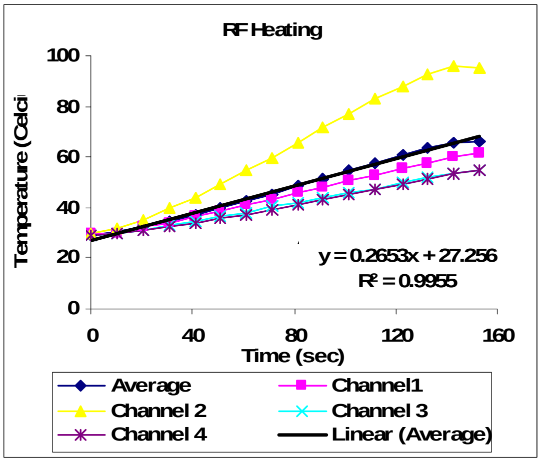

RF Heating
Temperature (Celci
Time (sec)
0
20
40
60
80
0
20
40
60
80
100
y = 0.2828x + 26.189
R^2 = 0.9958
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

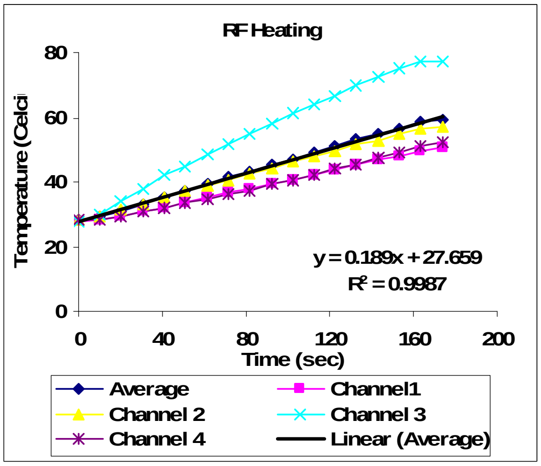

RF Heating
Temperature (Celci
80
60
40
20
0
0
40
80
120
160
Time (sec)
y = 0.2238x + 21.344
R² = 0.9952
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

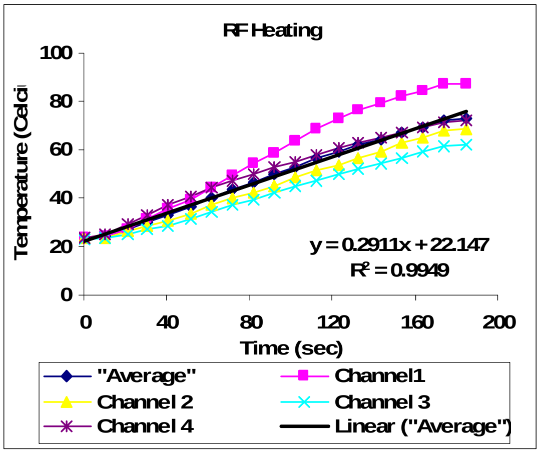

RF Heating
Temperature (Celci
100
80
60
40
20
0
0
40
80
120
160
Time (sec)
y = 0.2939x + 27.08
R² = 0.9923
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

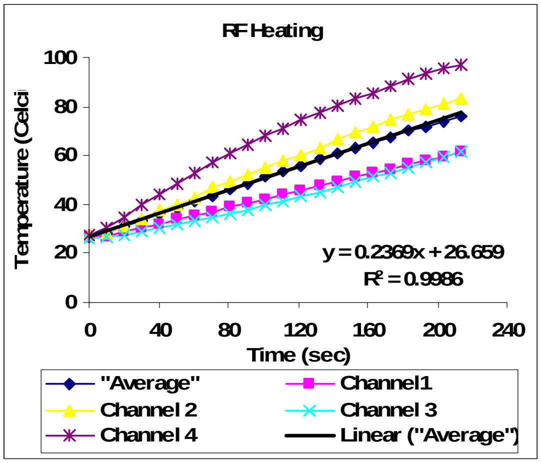

RF Heating
Temperature (Celci
80
60
40
20
0
0
40
80
120
160
200
Time (sec)
y = 0.1589x + 25.938
R² = 0.9966
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

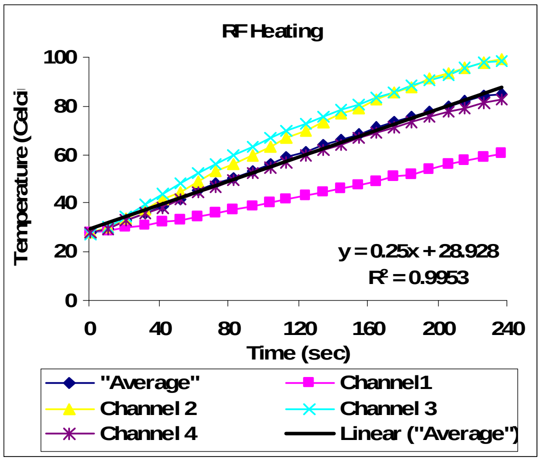

RF Heating
Temperature (Celci
100
80
60
40
20
0
0
40
80
120
160
200
Time (sec)
y = 0.2038x + 29.719
R² = 0.9884
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

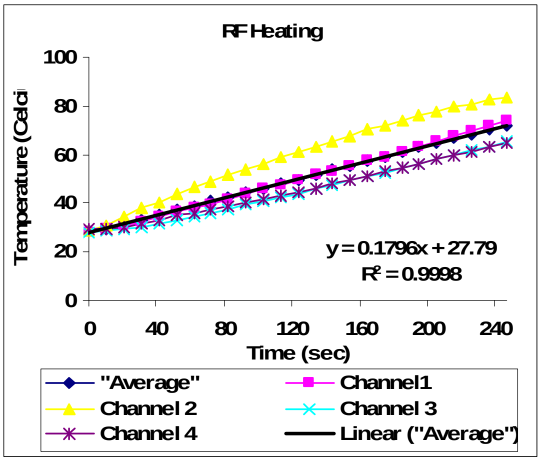

RF Heating
Temperature (Celci
100
80
60
40
20
0
0
40
80
120
160
Time (sec)
y = 0.2653x + 27.256
R² = 0.9955
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

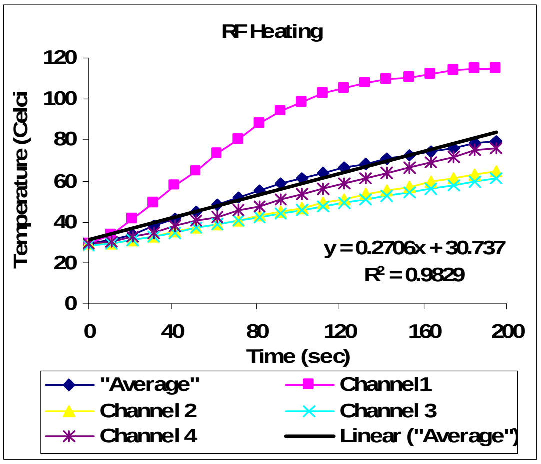

RF Heating
Temperature (Celci
80
60
40
20
0
0
40
80
120
160
200
Time (sec)
y = 0.189x + 27.659
R² = 0.9987
Average
Channel1
Channel 2
Channel 3
Channel 4
Linear (Average)

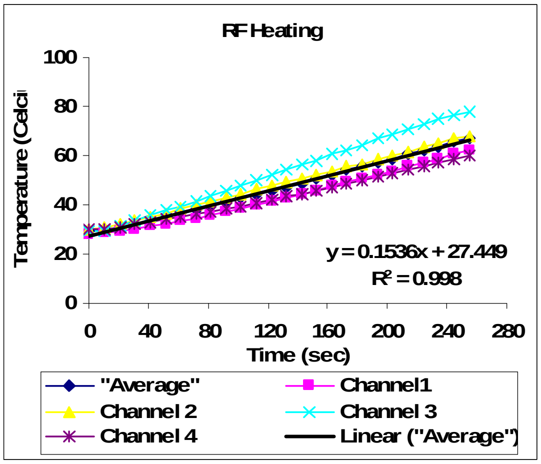

RF Heating
Temperature (Celci
Time (sec)
100
80
60
40
20
0
0
40
80
120
160
200
y = 0.2911x + 22.147
R^2 = 0.9949
"Average"
Channel1
Channel 2
Channel 3
Channel 4
Linear ("Average")


RF Heating
Temperature (Celci
Time (sec)
100
80
60
40
20
0
0
40
80
120
160
200
240
y = 0.2369x + 26.659
R^2 = 0.9986
"Average"
Channel1
Channel 2
Channel 3
Channel 4
Linear ("Average")


RF Heating
Temperature (Celci
Time (sec)
100
80
60
40
20
0
0
40
80
120
160
200
240
y = 0.25x + 28.928
R^2 = 0.9953
"Average"
Channel1
Channel 2
Channel 3
Channel 4
Linear ("Average")


RF Heating
Temperature (Celci
Time (sec)
100
80
60
40
20
0
0
40
80
120
160
200
240
y = 0.1796x + 27.79
R^2 = 0.9998
"Average"
Channel1
Channel 2
Channel 3
Channel 4
Linear ("Average")


RF Heating
Temperature (Celci
Time (sec)
120
100
80
60
40
20
0
0
40
80
120
160
200
y = 0.2706x + 30.737
R^2 = 0.9829
"Average"
Channel1
Channel 2
Channel 3
Channel 4
Linear ("Average")


RF Heating
Temperature (Celci
Time (sec)
100
80
60
40
20
0
0
40
80
120
160
200
240
280
y = 0.1536x + 27.449
R^2 = 0.998
"Average"
Channel1
Channel 2
Channel 3
Channel 4
Linear ("Average")