Biological effects and application of non-ionizing microwave radiation

by

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A Project Report Submitted in Partial Fulfillment
of the Requirements for the Degree of

MASTER OF ENGINEERING

in the Department of Electrical and Computer Engineering

Supervisory Committee

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Abstract

Electromagnetic radiation is the basic building block of a wireless communication system. With the increase in the utilization of communication systems, it is necessary to investigate the effects of such radiation on human beings as it can cause health issues. High frequency ionizing microwave radiation has been used for medical purposes including cancer treatment which tend to be invasive.

In this project, a new model is proposed as a non-invasive hyperthermia cancer treatment. This model consists of two sub-models. It operates at a frequency of 60 GHz and is compared with 2.45 GHz systems which are used for invasive hyperthermia treatment. Simulation results prove that a 6 kelvin temperature increase is achieved using 60 GHz with an uncharged particle model at approximately 10 kW/m^2 power density. Simulation results also prove that 2.45 GHz shows negligible temperature increase. This makes the 60 GHz uncharged particle model a better solution for non-invasive hyperthermia treatment.

Simulation results based on the proposed model also prove that communication systems utilizing 60 GHz are safe for public and commercial deployment while operating in compliance with standard industry power density limits. It is proven by simulation results that at a power density of 10 W/m^2 and 50 W/m^2, which are specified by FCC and ICNIRP as maximum power densities for the general public and occupational groups, respectively, the temperature increase in the particle is in the range of milli to micro kelvin. This negligible increase confirms that 60 GHz communication systems operating at low power density have no thermal effects on the human body while 60 GHz systems can be used for hyperthermia treatment at high power density.

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Acknowledgments

I would like to thank my graduate supervisor Dr. Reuven Gordon for his support, motivation,, and guidance to my studies and all those friends who helped me whenever I needed help.

I would like to thank Dr. Jens Bornemann for serving on my supervisory committee.

Dedication

I would like to dedicate my report to my family for their support and encouragement at all stages of my life.

Chapter 1

1.1 Introduction

High speed wireless systems are shifting towards high frequency microwave bands. That is all made possible by the advancement in millimeter wave electronics [1-6]. A growing number of communication systems operating at microwave frequencies have motivated researchers to understand how microwave radiation and biological systems interact. Biological tissues interaction with microwave radiation is dependent on radiated power and can be divided into two subgroups.

1) High power systems that can induce sufficient heating on human body surfaces, example 94 to 95 GHz active denial system and therapeutic applications operating at 42.25, 53.57, and 61.22 GHz [7].
2) Although the communication systems and radar systems operating at low power in V (40-75 GHz) and W (75-110 GHz) bands do not cause any significant temperature increase in human tissues, prolonged exposure may cause biological and health effects.

The unlicensed sub-band (57 to 64 GHz) is particularly important for high speed short range communication that is used for point to point and point to multipoint communications [8-12]. 60 GHz band radiation has never been exposed to the human body in natural circumstances since this frequency is located around the peak of molecular oxygen absorption, and it is highly attenuated in the atmosphere [13].

Few theories have been presented to describe how microwaves can have potential biological effects on the human body [14]. Some experiments show that microwave radiation can interfere with some cellular processes when certain exposure conditions are applied [15].

Several environmental elements can cause organizational and conformational changes in biological molecules. Cellular components that are affected by the physical and chemical changes are DNA and proteins. Damages to the DNA are caused by high energy treatments (e.g. ionization radiations), and proteins are affected by weak uncontrollable treatments such as heat [17]. Microwaves are non-ionizing radiations, and they are not genotoxic [16]. These radiations might change protein conformations, and protein denaturation caused by environmental elements can produce biological impacts, and it can also induce cellular dysregulations, cellular organization or cell growth [17].

It is necessary to investigate potential biological effects of the 60 GHz band before it can be utilized in commercial and residential deployment, and a potential hyperthermia treatment. The impact of 2.45 GHz used for hyperthermia cancer treatment also needs to be investigated and compared with the results of the 60 GHz frequency.

1.2 Organization of Report

The primary objective of this report is to study the temperature change caused by the thermal effects of microwave radiation by a frequency used for hyperthermia treatment and low power communication system.

Chapter 2 gives an overview of radio frequency, electromagnetic frequency spectrum, power density, ionizing and non-ionizing radiation, and microwave energy.

Chapter 3 discusses thermal and non-thermal effects of microwaves and hyperthermia as the application of microwave radiation. Chapter 3 also includes far field and near field exposure of an antenna used in hyperthermia.

Chapter 4 consists of proposed model, and results. Chapter 5 provides conclusion and future work.

Chapter 2

2.1 Radio Frequency

Radio waves and microwaves are electromagnetic energies defined by the term radio frequency (RF). Radio frequency emission can be described in terms of energy, radiation, or fields. Radiation can be described as the propagation of energy in the form of waves through space. Electromagnetic radiation is the combined movement of electric and magnetic waves through space, and they are produced by moving electrical charges in a conducting material. These electromagnetic waves are characterized by wavelength and frequency. Radio frequency is measured in terms of volts per meter (V/m) for the electric field and amperes per meter (A/m) for the magnetic field.

2.2 Electromagnetic frequency spectrum

The electromagnetic spectrum consists of a range of electromagnetic waves which increase in frequency. These frequencies rise from an extremely low frequency and very low frequency (ELF&VLF) at the bottom, and then through radio frequency (RF), and microwaves to infrared light (IR), visible light, and ultraviolet light (UV), X-rays and gamma rays at the very extreme [18].

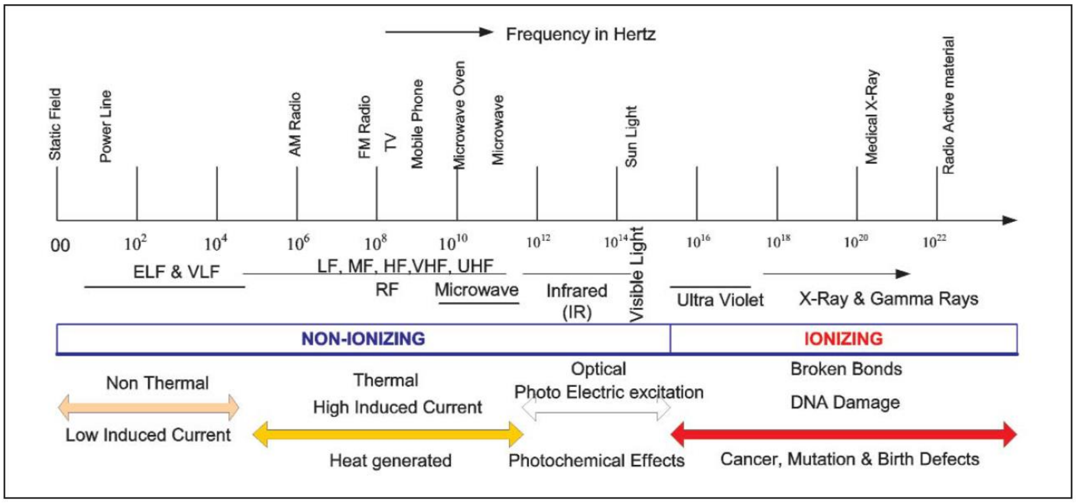

Figure 1: Electromagnetic spectrum [18]

2.3 Power Density

Power density is the measurement of an electromagnetic field at a point in space and is defined as power per unit area normal to the direction of propagation. Power density is expressed in units of Watts per square meter (W/m^2). Power density, electric field strength (E), and magnetic field strength (H) are related by the free space impedance, i.e. 377 ohms (Ω) [66].

Power density is related to electric field strength (E) and magnetic field strength (H) as

$$P_D = \frac{E^2}{377\Omega} = 377\Omega H^2. \tag{2.1}$$

Power density is related to transmitted power as

$$P_D = \frac{P_T}{4\pi r^2}, \tag{2.2}$$

where $P_D =$ power density in watts / meter^2, $P_T =$ transmitted power in watts, and $r =$ distance in meters.

2.4 Power Density Exposure Limits

Power density is a preferred metric of exposure compliance determination at higher frequencies. Power density limits set by Federal Communication Commission (FCC) and International Commission on Non-Ionizing Radiation Protection (ICNIRP) is 10 W/m^2 and 50 W/m^2 for the general public, and occupational group respectively [94]. ICNIRP power density restrictions are specified for frequencies between 10 GHz and 300 GHz [94]. FCC power density exposure is defined for frequencies between 6 and 100 GHz [95].

2.5 Ionizing Radiation

Electromagnetic waves contain sufficient energy to remove atoms and molecules from tissues and consequently change the chemical reactions in the human body. Such radiations are known as ionization radiation. X-rays and Gamma rays are forms of ionization radiation [18].

Low levels of ionization radiation from natural sources are always affecting natural environments around human beings. Primary sources of such radiation are visible light, ultraviolet light, infrared light, cosmic rays from outer space and the human body’s natural radioactivity [18].

2.6 Non-ionizing Radiation

Electromagnetic radiation with inadequate energy to cause effects at the atomic level is considered as non-ionizing radiation. Following are some non-ionizing radiations:

- 0 Hz direct current static electromagnetic field;
- 50 to 60 Hz electric power low frequency waves;
- Up to 30 KHz extremely low frequency and very low frequency fields;
- 30 KHz to 300 GHz Radiofrequency, microwave and millimeter wave;
- Beyond 300 GHz infrared light, visible light and ultraviolet light.

Excessive exposure to high power densities can cause potential health hazards. Following are some health hazards that have been suggested [18]:

- Cancer;
- Tumors;
- Headaches;
- Fatigue;
- Alzheimer's disease;
- Parkinson's disease.

Radio frequency is characterized as non-ionizing radiation as there is not enough energy in a single quantum of energy, hf, to ionize an atom or a molecule, where h is Plank's constant and f is the frequency. The energy of electromagnetic waves can be expressed in electron volts which are multiple of kinetic energy obtained by an electron through a potential difference of 1eV (1 eV = 1.6×10^{-34} J s). Ionization potential is the energy required to remove one electron from the highest energy orbit of a particular chemical, for the hydrogen atom it is 13.6 eV and for gaseous sodium it is 5.1 eV [65].

High frequency microwaves (millimeter waves) have a quantum energy of 1.2×10^{-4} to 1.2×10^{-3} eV [50]. Average thermal kinetic energy of particles is related to temperature by [64]:

$$W = kT, \tag{2.3}$$

where k is the Boltzmann's constant (1.38 x 10^{-23} J/K). Putting the value of k in (2.3) results in

$$1.38 \times 10^{-23} T \approx 5.1\, eV \approx 5.1 \times 1.6 \times 10^{-19}\, J$$

$$\mathrm{T} \approx 5.1 \times 10^{4} K$$

which is twice the temperature inside a lightning strike, and it is orders of magnitude higher than an electromagnetic wave traveling through the air [63].

2.7 Microwave Energy

Dielectric properties play a vital role in determining the interaction between a microwave field and tissues, whereas the knowledge of physical properties of water and dielectric properties of the biological sample provides the basis for thermal applications of microwaves [62].

Complex permittivity, ε^*, represent permittivity and conductivity for a sinusoidal field of frequency f [62]. Mathematically,

$$\varepsilon^* = \varepsilon' - j\varepsilon'', \tag{2.4}$$

where $\varepsilon'' = \frac{\sigma}{\omega \varepsilon_0}$ and $\omega = 2\pi f$.

The real part, ε', is specified as relative permittivity, and the phase of the transmitted wave and energy stored is associated with relative permittivity. The imaginary part, ε'', is known as dielectric loss, and the amplitude and power absorption of electromagnetic field interaction with the matter is influenced by dielectric loss [62].

When a constant voltage is applied to a simple system, the system which is initially at equilibrium responds with an exponential function of time which may be the cause of charge build up between two different dielectric interfaces [62]. The system relaxes exponentially when the voltage is removed.

When an alternating voltage is applied the complex permittivity of a simple system varies with frequency [62], and can be written as

$$\varepsilon^*(\omega) = \varepsilon_\infty + \frac{\varepsilon_S - \varepsilon_\infty}{1 + j\omega\tau}, \tag{2.5}$$

where τ is the time constant of the exponential relaxation process, $\varepsilon_\infty$is the permittivity at $\omega \ll \frac{1}{\tau}$, and ε_S is the permittivity at $\omega \gg \frac{1}{\tau}$. This is the Debye dispersion equation [62].

The Debye equation can be separated into real and imaginary parts as

$$\varepsilon' = \varepsilon_\infty + \frac{\varepsilon_S - \varepsilon_\infty}{1 + (\frac{f}{f_c})^2}, \tag{2.6}$$

$$\varepsilon'' = \frac{(\varepsilon_S - \varepsilon_\infty) f/f_c}{1 + (f/f_c)^2}, \tag{2.7}$$

or

$$\sigma_d = \frac{(\varepsilon_S - \varepsilon_\infty)2\pi\varepsilon_0 f^2}{f_c(1 + (\frac{f}{f_c})^2)}, \tag{2.8}$$

where the characteristic frequency $f_c = \frac{1}{2\pi\tau}$, and subscript d denotes the conductivity due to a Debye relaxation process.

Figure 2 shows the dependence of complex dielectric permittivity of water on frequency at different temperatures. Real and imaginary parts are represented as dielectric constant and loss factor, respectively.

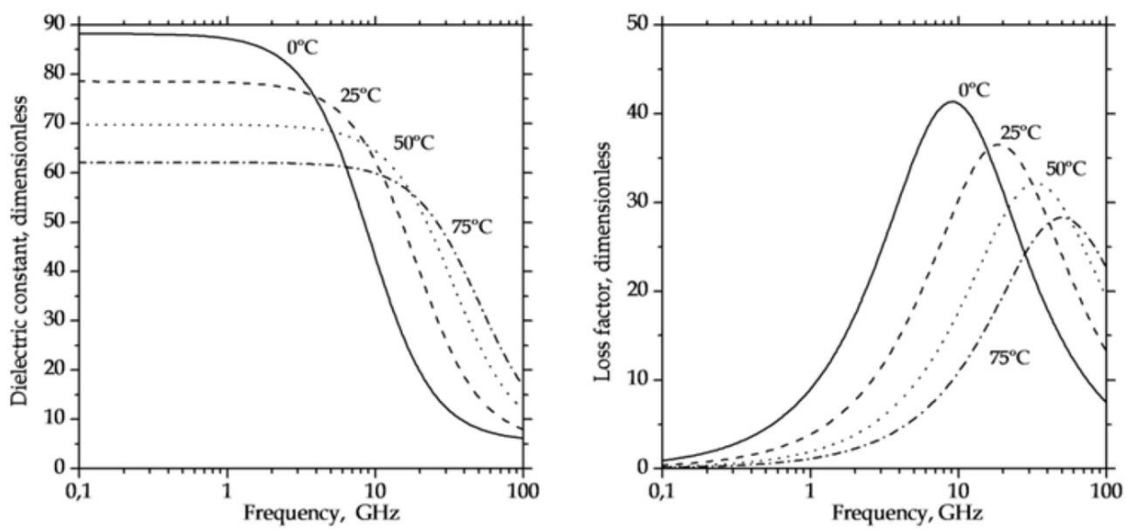

Figure 2: Dependence of complex dielectric permittivity of water on frequency [41]

Chapter 3

3.1 Thermal Effects

The kinetic energy of the molecules is increased by RF power which transforms energy entering into tissues and generates heating in the absorbing medium. Heating is caused by ionic conduction and vibration of dipole molecules of water and proteins [19]. A rise in temperature caused by the power absorption is dependent on the cooling mechanism of the absorbing medium. Fields generating heat are dependent on frequency, source configuration, dielectric properties of tissues and tissue geometry [19]. Exceeding the thermoregulatory capability of the tissue will cause tissue damage which occurs at the absorbed power levels beyond the metabolic power output of the body [19]. The steady increase in absorbed energy causes break down in protective mechanism for heat control, consequently, body temperature rises uncontrollably. These effects have been seen in dogs and rats [20-22]. Tissues with high water content experience high energy absorption and low depth of penetration, while absorption is lower in tissues with low water content such as fat and bone [19]. Hot spots which are caused by standing waves can be produced in the tissues. These spots are caused by the reflection between interfaces of different water content, and these standing waves are independent of dielectric constant or conductivity. Animals exposed to microwave power showed skin burns over their rib cage [19]. Deep penetration of energy causes microwave burns to deepen. The most vulnerable tissues are those with poor blood circulation or temperature regulation, such as eye lens and gallbladders [19]. RF heating has been used for therapeutic purposes by medical professionals also. These therapeutic temperatures range very close to a temperature range (43℃ to 45℃) which can cause harmful changes, and this technique is called diathermy [19]. Possible enzyme reactions can alter the metabolic rate and proteins may be denatured [19].

3.2 Non-thermal Effects

Non-thermal effects are not related to the increase in the temperature. This effect can be associated with the forces acting on the particles and is called pearl chain effect [23-27]. Particles form a chain parallel to the electric line of forces, and there is a frequency range where the effect occurs at minimum field strength for each type of particle. Chain development is due to the attraction between particles in which dipole charges are induced by RF fields [28-31]. Hydrogen bond destruction is possible as these fields can line up polarized side chains of molecules with the direction of electric field [32]. It was experimentally confirmed that these effects can denature or coagulate molecules [33]. A non-thermal irreversible inactivation of few enzymes has been demonstrated after they were exposed to 10.4 GHz microwave radiation [34].

3.3 Hyperthermia

Hyperthermia is the treatment of specific parts of a body or a whole body for a defined period by increasing the temperature beyond normal [67]. By applying energy in the form of high frequency electromagnetic waves, any material can be heated. Heat has an intense effect on cells. An injury recovers faster when heat is applied at a low dose. At high doses, however, cells might die immediately [35]. These heating effects make heat treatment a potential against cancer, and effects of heat on cancer cells are well-known [36]. Heat causing cell death is a function of the intensity of applied heat and time of exposure [35]. Cells are killed by high dose-time combination by necrosis [37]. Mild exposure causes a cell to experience apoptosis, and insufficient heat causes a cell to become sensitive to radiation and drugs [38]. Cancer cells recover slower than normal cells when exposed to heat, normal tissues have more blood flow than cancerous tissues that makes normal tissues dissipate heat better [35]. Another reason for heat dissipation is greater diameters of blood vessels in cancerous tissues than normal tissues that make cancerous tissue occupy a greater volume than the normal tissue. During hyperthermia treatment, the temperature of cancerous tissues is greater than normal tissues because the conductivity of blood is higher for normal tissues [39].

Hyperthermia treatment is accomplished by heating the cancerous cells to a temperature greater than 42℃ without exceeding normal temperature ranges in healthy tissues which are lower than 42℃ [39]. If a temperature is lower than 42℃, there will be no heating effect on cancerous tissues and if a temperature is greater than 44 - 45℃, both healthy and infected cells are damaged [40].

Using low temperature (below 41℃) for approximately an hour for multiple sessions can be used for treating aches, pains, strains and sprains [68]. Exposure time can be reduced by half with 1℃ temperature rise at temperatures 42.5-43℃ [69]. Up to 44℃, healthy tissues are undamaged by treatment for 1 hour [42]. Cell death is probably caused by protein denaturation observed at temperatures > 40 ℃ which induces alterations in multimolecular structures and changes DNA synthesis and repair [70]. The thermal dose-response relation varies among cells and depends on environmental factors such as the pH value [71]. Protein damage is the primary biological effect of hyperthermia in the clinical therapeutic temperature range of 39 to 45℃. Protein denaturation and cell death induced by heat dwell in the same range of activation energies [42, 43]. Thermal effects cause destruction in cells and tissues by protein denaturation [72].

3.4 Hyperthermia heating systems

A typical hyperthermia system exposes intended body surface to electromagnetic fields or ultrasound radiation. To transfer energy into biological tissue, a structure is required. External applicators are used to transfer energy in common hyperthermia treatment [73-75].

The applicators are placed in such a way to focus energy on the tumor to raise the temperature of the tumor. In a non-invasive hyperthermia treatment, magnetic resonance image (MRI) can be incorporated into hyperthermia systems to detect treatment temperature.

3.4.1 Ultrasound

Propagation of sound waves at a frequency of 2 to 20 MHz is called ultrasound wave. These waves are absorbed by the tissues and result in heating of the absorbing medium. A shortcoming of the ultrasound system is a weakness to perforate through air and trouble in bone penetration [67].

3.4.2 Radiofrequency (RF)

To heat large tumors, radiofrequency is used in the range of 10 to 120 MHz as its wavelength is long compared to the dimension of a human body, and it can store energy over a large volume of the body [76].

3.4.3 Microwaves

Microwave hyperthermia is the most commonly used technique and it has been used on thousands of patients [67]. The microwave generated heat is used to shrink and destroy cancerous tumors, and it commonly uses a single waveguide microwave antenna operating at 434, 915 and 2450 MHz. A microwave hyperthermia system includes the antenna and a non-contacting temperature sensor [67]. The microwave power supply to an antenna is adjusted using a feedback loop controller which detects the temperature of the body, and the temperature sensor is utilized for this purpose. Blood flow is increased in the tumor which is poorly oxygenated by microwave hyperthermia.

3.5 External RF Applicators

3.5.1 Capacitive Heating

An RF approach that is commonly used for clinical purposes is the capacitively coupled system. The capacitive hyperthermia systems are comprised of a radio frequency generator, a set of electrode applicators along with connecting cables, a temperature control system, an impedance matching network, a radio frequency power meter, and patient support structures [67].

The applicator is a two plate capacitor excited by an electric field potential between the plates. This capacitor plate operates in an ISM band which is assigned to industrial, scientific and medical applications, and their operating frequency is 13.56 or 27.12 MHz. Coaxial cables are used to transmit RF energy which is generated by the generator. These cables are connected to the electrodes fixed on the body. Interaction of electric field between opposed electrodes is used to disperse the power through the body [67].

3.5.2 Inductive Heating

A biological object is heated by transferring energy from a coil carrying alternating current through the air. It is used to achieve deeper hyperthermia [67]. Induced heat is maximum in the muscles instead of fat, and the simplest inductive applicator is a single co-axial current loop [77]. These applicators operate at ISM frequencies of 13.56, 27.12 and 40 MHz with a penetration depth of few centimeters. An induction hyperthermia system is comprised of an RF power generator, an RF power meter, an impedance matching network, one or more induction coil applicators and a set of connecting cables and a patient support assembly [67].

3.5.3 Capacitive and Inductive Heating

Capacitive coupled electrodes and induction applicators are used in this hybrid heating structure. Electrodes and applicators generate currents which are added in the body under treatment [78].

3.6 External radiative EM devices

Electromagnetic devices used for high frequency hyperthermia treatment are limited in penetration depth, and only 2-3 cm deep tumors can be heated with surface applicators [79]. Waveguides and horns [80-83] and micro strip patches [84-87] can be used as different types of applicators. These applicators can converge microwave energy up to 6 cm in a lossy medium like human muscle [88].

3.6.1 Single applicators

Single aperture devices were used in early hyperthermia trials, these devices lacked the ability to focus energy. 27 MHz ridged waveguide [80], 82 MHz helix [89], 70 MHz coaxial TEM applicator [81-83] were tested as a single applicator. Accurate thermal doses to small tumors can be delivered by single element applicators [67].

3.6.2 Multi element array applicators

An array applicator provides deep penetration depth while reducing undesired heating of surrounding tissues and improves control of tumor temperature. Heat is delivered across the larger area by these RF devices, shallow penetration at high frequency requires the target to be compressed. During hyperthermia treatment, the microwave array system can add more control to the heating arrangement by utilizing applicators of different phase, frequency, amplitude and applied field orientation [90]. Electromagnetic phased array hyperthermia faces two challenges [91, 92]

1. Increasing the temperature of cancerous tissue without harming surrounding healthy tissues while electrical and thermodynamic inhomogeneity exists.
2. Reaction to change in patient positioning that can significantly affect treatment.

3.7 Far-field exposure

A directive antenna is used under free space conditions for exposing biological samples [17, 51, 52]. Finite difference time domain (FDTD), finite element method (FEM) and finite integration technique (FIT) have been applied to analyze the power density distribution in the sample under test [53, 54]. Far field exposures have low exposure efficiency (10-15%). For an antenna to achieve high power density, there are two possible ways:

1. Increase the output power;
2. Decrease the distance between antenna and sample.

The first solution requires high power generators [55, 56], and the second solution suggests placing the biological sample in the reactive zone of near field distribution [57].

3.8 Near-field exposure

Near field exposures offer better exposure efficiency and result in high power density levels absorbed by the biological sample. Millimeter wave exposure at 61 GHz has been implemented by few studies in near-field configuration [58].

3.9 Penetration Depth

The distance at which power density is decreased by the factor e^{-2} is called penetration depth (δ) of energy. Power density is inversely proportional to attenuation factor (α), and microwave energy decreases as it travels into the material.

$$\alpha = \frac{1}{\delta}. \quad (3.1)$$

Penetration depth determines how much energy reaches into the body, the basic factor in determining penetration depth is the reflection at the external surface of a conducting body at a lower frequency along with a shunting of the electric field [62].

Chapter 4

4.1 Model

The basic purpose of this model is to find the power density required to increase the temperature by 6 kelvins in a particle under test. A particle is used here to replicate the effects of high power density on a human body. Assuming the initial temperature of the particle is normal human body temperature which is 310.15 Kelvin (37℃), increasing the temperature by 6 kelvins (43℃) induces heat into the particle under test and makes this model feasible for the hyperthermia treatment. The particle can be a protein (globular protein), and the increase in temperature denatures protein and kills the cancerous cell or makes it sensitive to the treatment.

The model consists of two submodels, uncharged and charged particle models. These sub models show the displacement observed in the particle. This displacement is then used to find the temperature change in both models by using the equipartition method [61].

A single 2.45 GHz waveguide is assumed to be an external radiative device. A microwave frequency of 2.45 GHz is being used for this model because it can be used as an external microwave device which is already a common hyperthermia treatment technique.

A complementary metal oxide semiconductor (CMOS) phased array antenna is assumed to be operating at 60 GHz [93].

The penetration depth of both frequencies varies in this treatment. In order to compare both models, it is assumed that the sample under test is in the far field of the transmitting waveguide/antenna on a petri dish. Sample under test will observe maximum power density when they are in direct contact with main lobe of transmitting antenna at operating frequencies of 2.45 and 60 GHz.

This model shows that when a particle is considered as an uncharged particle, it can be heated with microwave energy operating at 60 GHz and low power density, which makes it a potential method of treatment to be used for hyperthermia. This model also shows that when a particle is considered charged, it can be modeled using the ion forced vibration theory, and the results prove that 2.450 GHz electromagnetic radiation temperature increase is insufficient which makes the 60 GHz proposed model suitable for hyperthermia treatment. Finally, the same model is used to find the temperature increase in the particle while following the standard power density restrictions in low power communication at 60 GHz.

4.2 Uncharged Particle

Globular proteins are approximately spherical, so we consider an uncharged particle as a sphere of radius a with dielectric constant $\varepsilon_1$surrounded in a fluid (water) with dielectric constant ε_2. The fluid has zero viscosity, and an electric field E_0 is applied to the sphere in the direction of negative z as shown in figure 3.

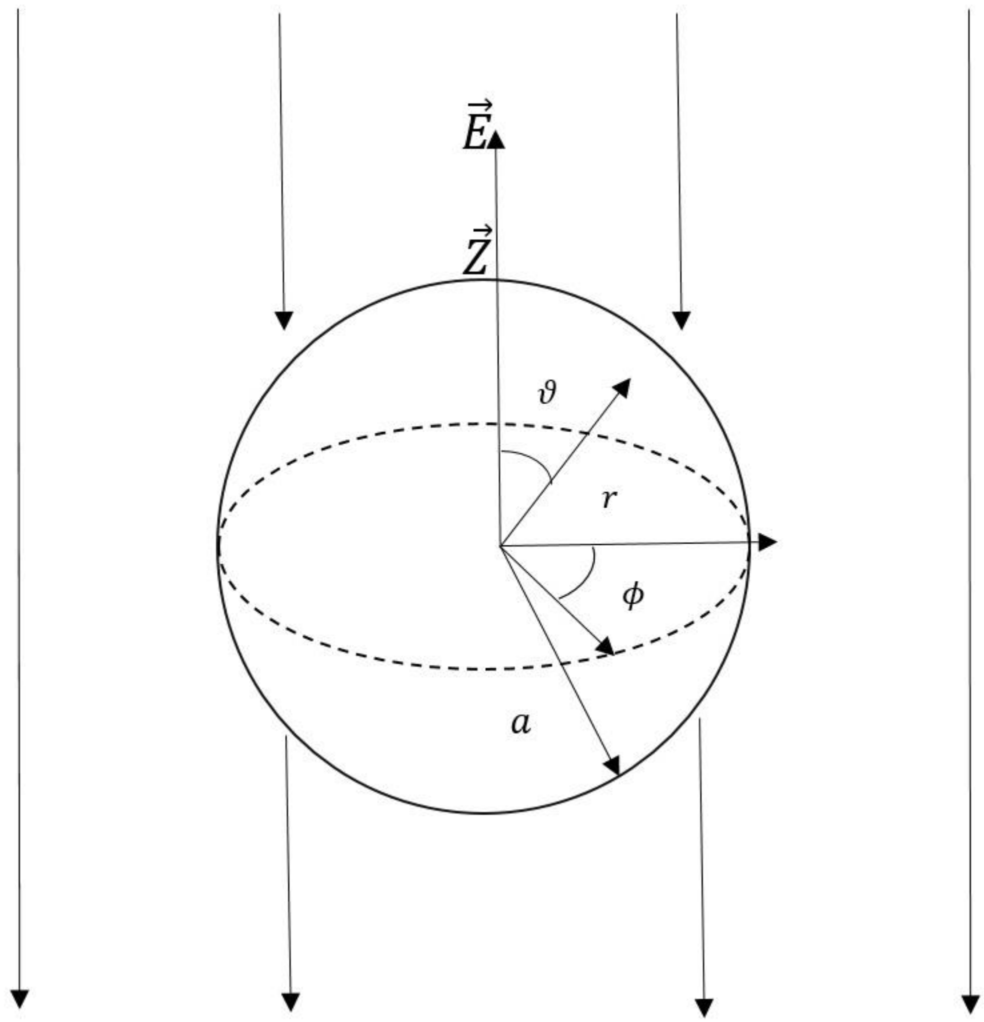

Figure 3: Sphere in the presence of electric field [48]

The electric field inside the dielectric sphere is uniform and parallel to the z-axis with its magnitude [46],

$$E = \frac{3\varepsilon_2}{\varepsilon_1 + 2\varepsilon_2} E_0 \tag{4.1}$$

The force exerted by the electric field on sphere will cause elastic deformation that is governed by the Navier Equation [47],

$$\nabla^2 u + \frac{1}{1 - 2v} \nabla\nabla . u + \frac{f}{G} = 0, \tag{4.2}$$

where u is the displacement in the dielectric sphere, v is the Poisson ratio, G is the shear modulus, and f is the body force [48]. Neglecting gravitational force, equation (4.2) becomes

$$\nabla^2 u + \frac{1}{1 - 2v} \nabla\nabla . u = 0. \tag{4.3}$$

The pressure acting on the dielectric interface of the sphere (sphere-fluid) is given as [48],

$$P = (A' - B')\cos(\vartheta)^2 + B', \tag{4.4}$$

where A' and B' are given as

$$A' = \left(\frac{3\varepsilon_2}{\varepsilon_1 + 2\varepsilon_2} E_o\right)^2 \left[\left(\frac{\varepsilon_1}{\varepsilon_2}\right)^2 (\alpha_2 - \beta_2) - \alpha_1 + \beta_1\right], \tag{4.5}$$

$$B' = \left(\frac{3\varepsilon_2}{\varepsilon_1 + 2\varepsilon_2} E_o\right)^2 (\beta_1 - \beta_2). \tag{4.6}$$

The constants α and β are given by the Clausius-Mossotti law [49],

$$\alpha = \varepsilon, \quad \beta = -\frac{\varepsilon_0}{6} ({\varepsilon_r}^2 - 2\varepsilon_r - 2). \tag{4.7}$$

Here ε_0 is the relative permittivity of vacuum, and ε_r is the dielectric constant.

Expanding the pressure P in terms of Legendre series results in

$$P = \sum Z_n P_n(cos\vartheta). \tag{4.8}$$

The coefficients A_n and $B_n$are determined as

$$A_0 = -\frac{(A' + 2B')}{12G(1+v)}, A_2 = -\frac{(A' - B'^{)}}{6Gr^2(5v+7)}, B_2 = \frac{(A' - B')(2v+7)}{6G(5v+7)}, \tag{4.9}$$

while the deformation can be found by

$$U_r = 2A_o(2v-1)r + (12A_2vr^3 + 2B_2r)\frac{1}{2}(3\cos(\vartheta)^2 - 1). \tag{4.10}$$

Let $(\vartheta = 0)$, then equation (4.10) becomes

$$x = 2A_o(2v-1)r + (12A_2vr^3 + 2B_2r). \tag{4.11}$$

Equation (4.11) describes how much displacement in the particle will be observed due to the applied electric field, and this displacement will be used to find the temperature change in the particle. U_r is replaced with x to show displacement. Electric field is parallel to z-axis that's the reason for assuming $\vartheta = 0$ in equation (4.11).

Deformation in the sphere will be two times in vertical axis than in horizontal axis, as shown in figure 4.

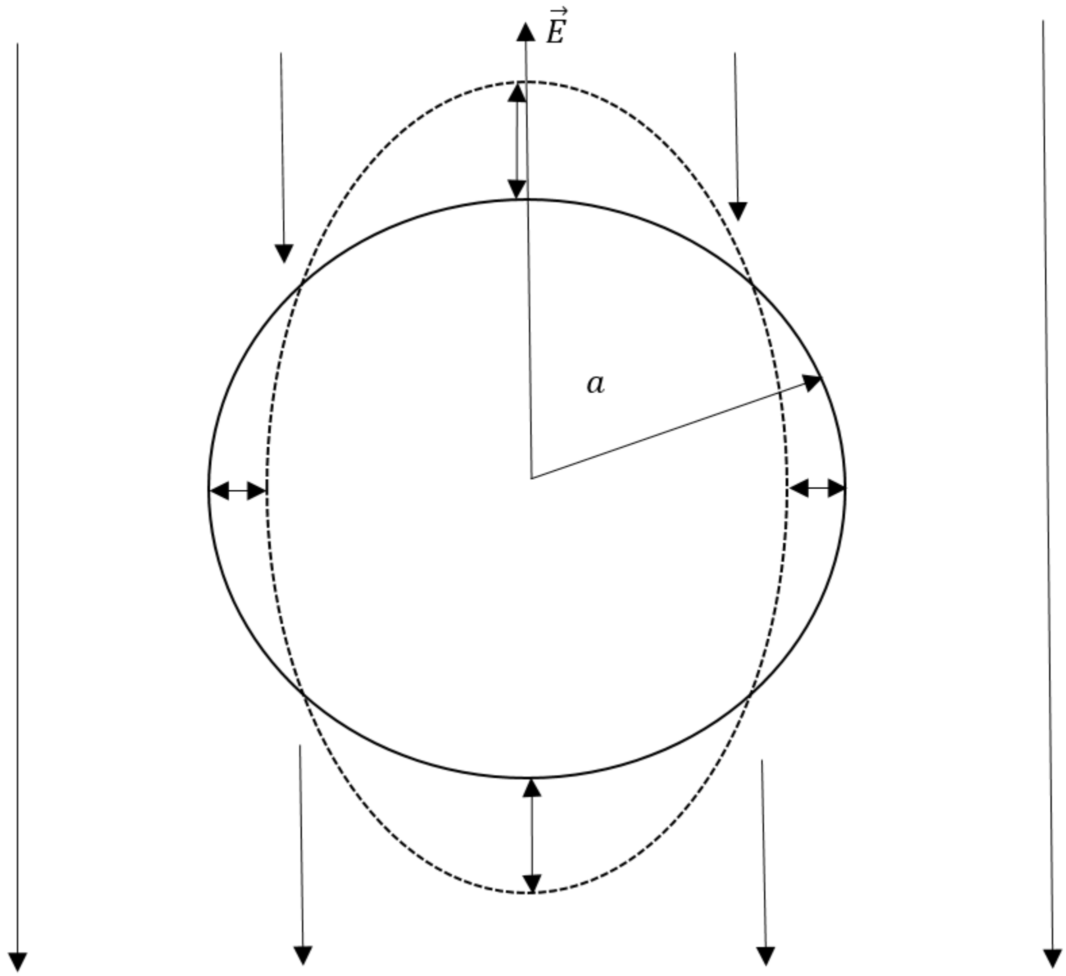

Figure 4: Deformed sphere in the presence of electric field

4.3 Charged Particle

The ion forced vibration theory states that even weak extremely low frequency electric fields of the order of 10^{-3} V/m can disrupt cell functions. Since radio frequency includes extremely low frequency, bio-effects of radio frequency can be explained by using this theory. The amplitude of any external oscillating electric or magnetic field when exceeding some critical value results in the changes in cellular functions and their accompanying biochemical processes.

The forced vibration of each free ion due to an oscillating field is given by the equation [59],

$$m_i \frac{d^2x}{dt^2} + \lambda \frac{dx}{dt} + m_i \omega_o^2 x = E_o z q_e sin\omega t, \quad (4.12)$$

where $E = E_o sin\omega t$ for an external oscillating electric field and circular frequency $\omega = 2\pi f$; z is the ion's valence; the charge carried by an electron or proton is $q_e = 1.6 \times 10^{-19}$ C; $F_2 = -m_i \omega_o^2 x$ is the restoration force proportional to displacement x of free ion's mass m_i ; $\omega_o = 2\pi f_o$ with f_o as the oscillation frequency of the ion after the displacement; the restoration force is negligible; $F_3 = -\lambda u$ is the damping force where $u = \frac{dx}{dt}$ is the velocity of ion; and λ is the attenuation coefficient for the movement of the ion.

Applying ion forced vibration theory to our model gives us the following equation.

$$m\frac{d^2x}{dt^2} + \gamma\frac{dx}{dt} + kx = zq_eE_o sin\omega t, \tag{4.13}$$

where $k = \omega_o^2 m$; m is the mass of particle oscillating at a circular frequency $\omega = 2\pi f$; k is the spring constant; z is assumed to be 1 in the case of hydrogen. Equation (4.13) can be written as

$$-\omega^2 mx + (-i\omega x\gamma) + \omega^2 mx = qE_o cos\omega t. \tag{4.14}$$

The displacement due to an external oscillating electric field on a charged particle at resonant frequency ω_r can be written as

$$x = \frac{qE_o 2Q}{k} cos\omega_r t, \tag{4.15}$$

where Q is the quality factor [60],[96], $\frac{1}{\gamma} = \frac{2Q}{\omega_r}$ and $\omega_r^2 m = k$.

For finding the change in temperature, it is assumed that the displacement in the particle causes the elastic potential energy to change and the equipartition method [61] is used to find the temperature change. Consider that the sphere stretches or compresses as a spring, so the amount of elastic potential energy depends on the displacement of the particle, which will convert its energy into kinetic energy and is given by the following equation

$$U = \frac{1}{2}kx^2, \tag{4.16}$$

where k is the spring constant (N/m), and x is the stretching or compression that a sphere will observe. Following the relationship between the spring constant k, motion of sphere x, Boltzmann's constant k_b and temperature T is given as [61]

$$\frac{1}{2}k(x)^2 = \frac{1}{2}k_b T. \tag{4.17}$$

Let $T = \Delta T$, equation (4.17) becomes,

$$\Delta T = \frac{k}{k_b}(x)^2. \tag{4.18}$$

Here the unit of temperature is Kelvin.

4.4 Results

The following table shows the values used in the simulation

Table 1: Parameter values

Parameter	Value
Protein radius a	1.7×10^{-9} m
Dielectric constant of protein ε_1	13 [44]
Dielectric constant of water ε_2	11.17 @ 60 GHz [45]
Dielectric constant of water ε_2	76.66 @ 2.45 GHz [97]
Poisson ratio v	0.33
Shear modulus G	1.015×10^{9} Pa
Permittivity of vacuum ε_0	8.85×10^{-12} F/m
Mass of protein m	20 kDa $\cong 3.32 \times 10^{-23}$ kg
Spring constant k	0.0079 N/m @ 2.45 GHz 4.71 N/m @ 60 GHz
Boltzmann's constant k_b	1.380×10^{-23} J/K
Quality factor Q	41 [60]

Figure 5 shows the relation between an applied electric field and power density in the spherical uncharged particle surrounded by water. It is evident from the figure that the dielectric constant of water at both frequencies shows an exponential increase in power density for applied E-field and at low frequency, the power density at the particle is approximately two times higher than that at high frequency which means that low electric field intensity can acquire better power density at low frequency.

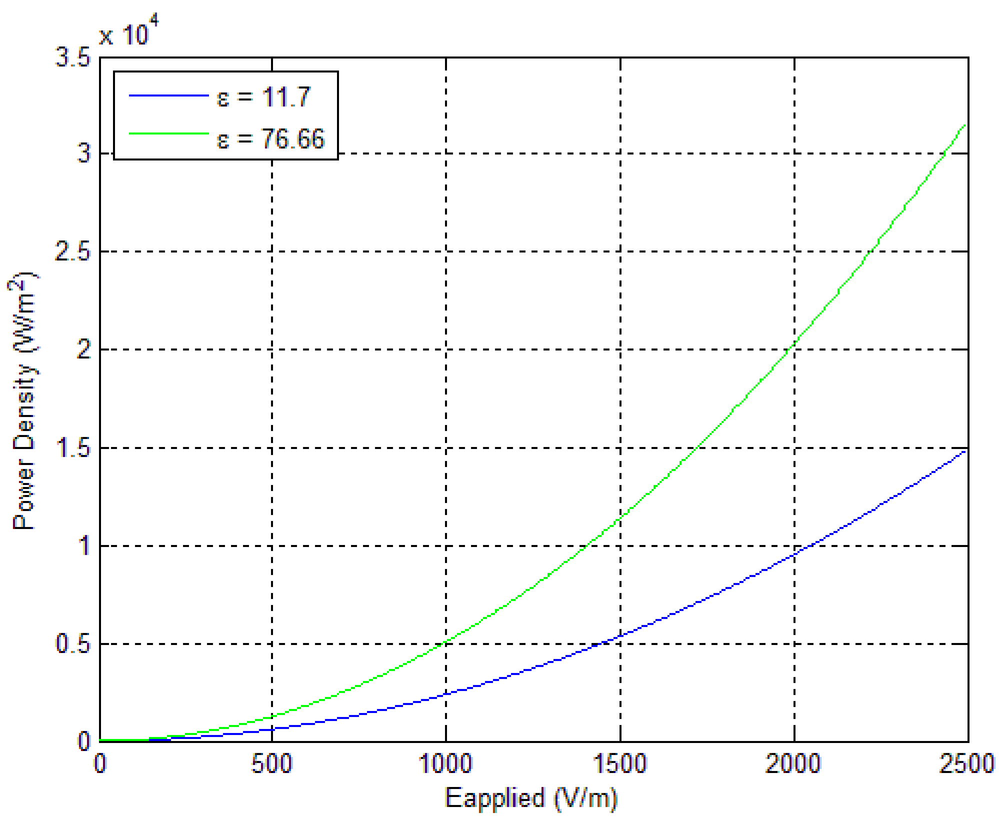

Figure 5: Electric field relation with power density in uncharged particle

Figure 6 shows the change in temperature in a particle. The temperature of the particle is assumed to be 310.15 kelvins (37 °C); both particle models are being compared to show 6 K (43°C) increase in temperature. Results show that 60 GHz frequencies can be used for the hyperthermia treatment with the uncharged particle model at approximately 10 kW/m^2 power density. The charged particle model does not show a significant increase in temperature.

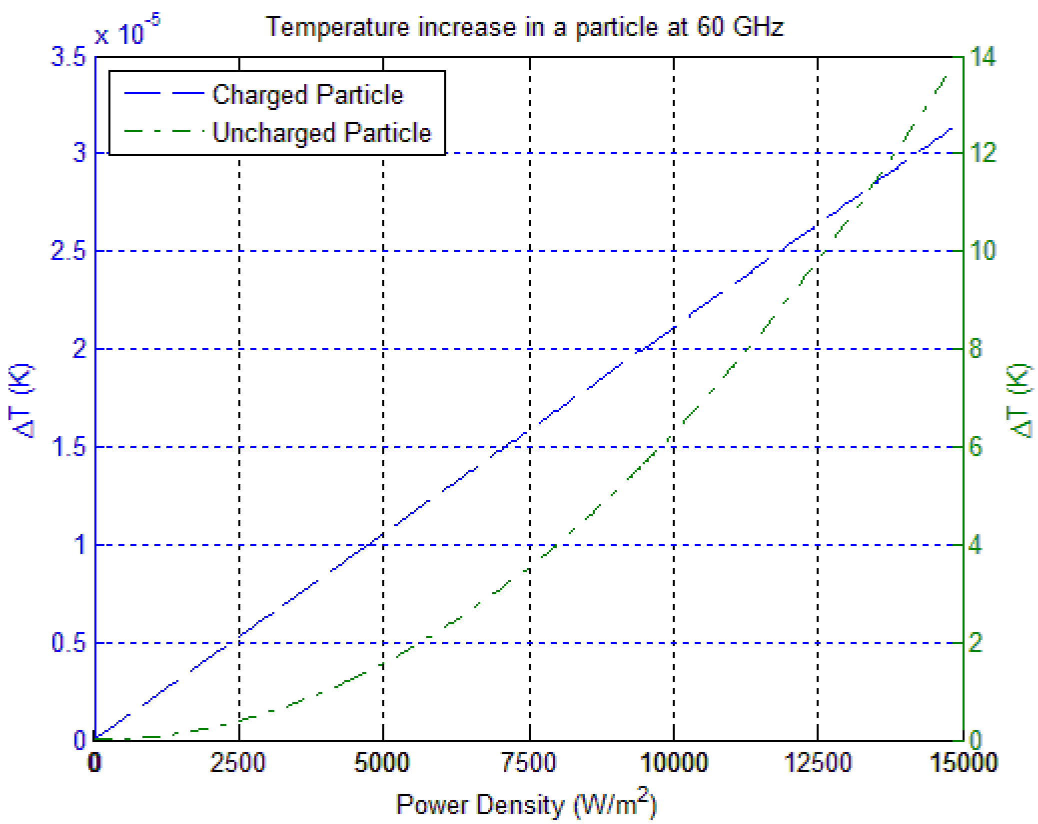

Figure 6: Temperature increase in a particle at 60 GHz

Figure 7 shows the increase in temperature at 2.45 GHz, and both particle models are compared. It is evident from the results that a 2.45 GHz frequency is incapable of causing any significant temperature increase at high power density. Temperature increase attained at high power density causes a negligible temperature increase in the particle. These results also confirm that the currently used frequency for hyperthermia treatment cannot be used with the proposed model.

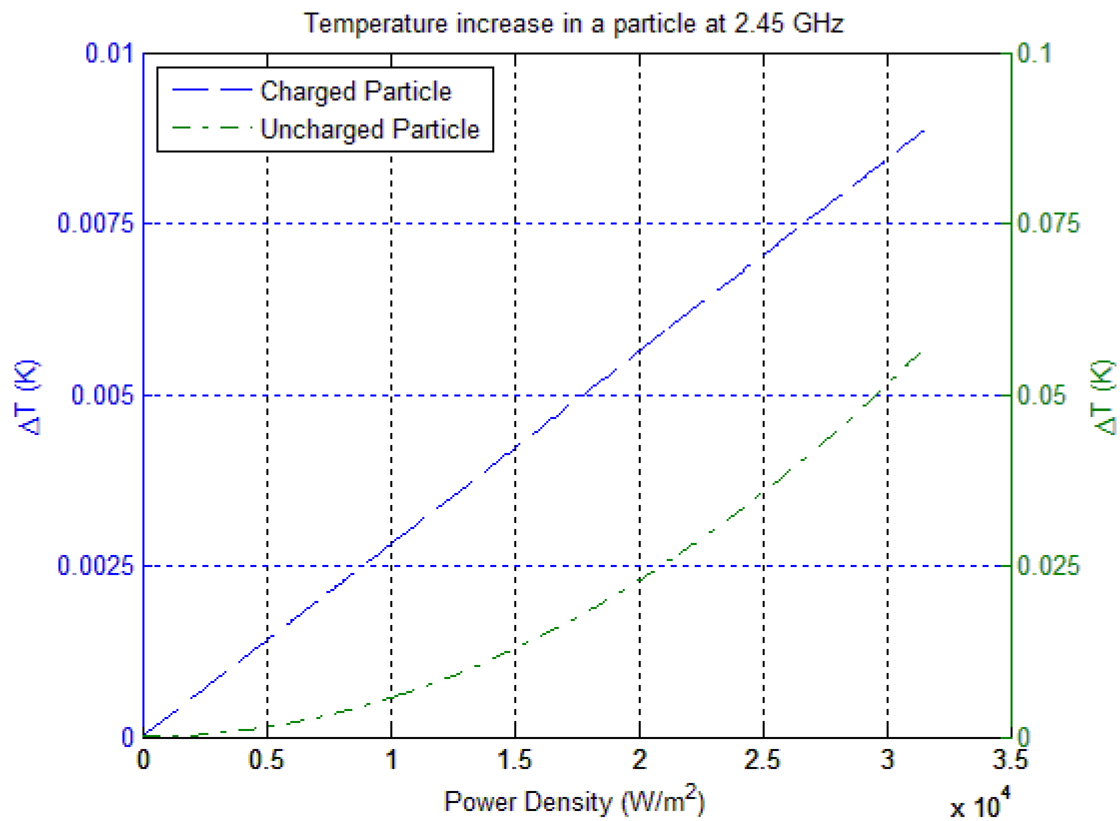

Figure 7: Temperature increase in a particle at 2.45 GHz

Figure 8 shows the increase in temperature at 60 GHz for both models. Results prove that the 60 GHz frequency induces negligible temperature increase in a particle; results also confirm that 60 GHz low power communication systems are safe for public and commercial deployment when such communication systems comply with FCC and ICNIRP power density restrictions.

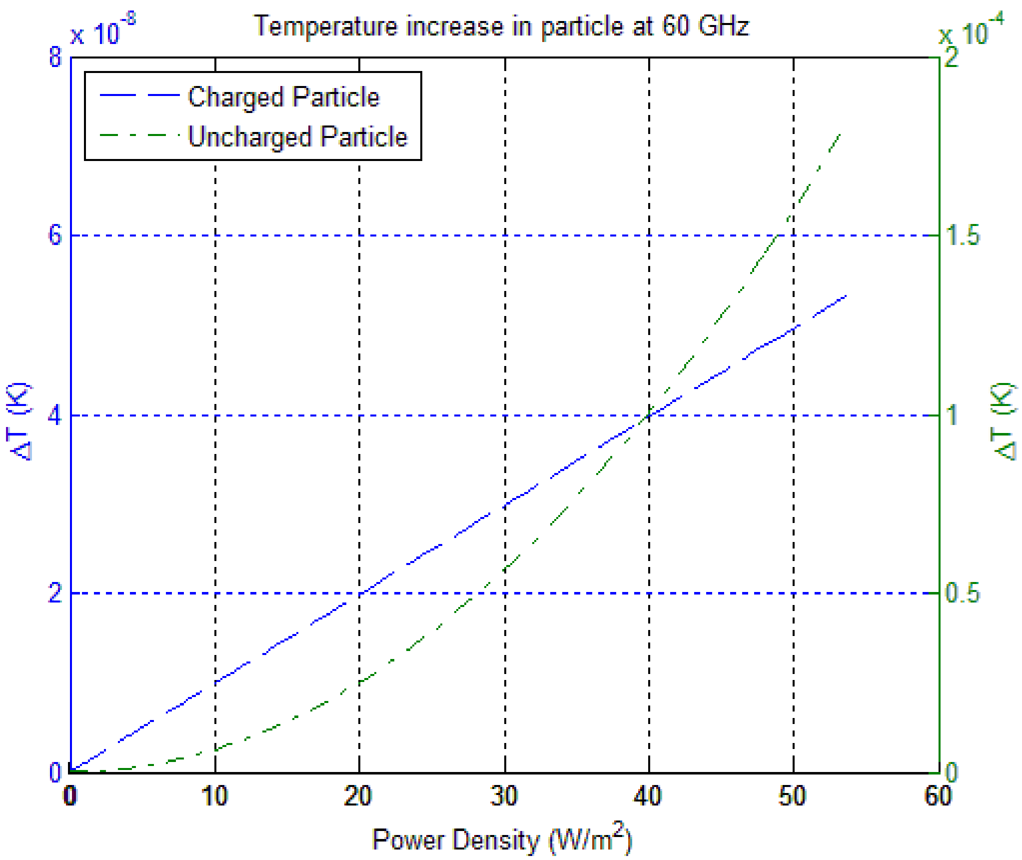

Figure 8: Power density compliance at 60 GHz

Chapter 5

5.1 Conclusion

This work presents a non-invasive method for hyperthermia which makes it practical for use in cancer treatment at approximately 10 kW/m^2 power density. Microwave radiation is non-ionizing and hence requires high power density to heat a biological sample. The proposed model can be implemented using a novel radiating system with high directivity antenna, and biological samples can be tested for the temperature rise in a nanoparticle like a globular protein.

Simulation results provide power density requirement for hyperthermia treatment but lacks the dose-time combination, therefore it is necessary to validate the model using hardware.

It is also shown that the 60 GHz band induces negligible temperature increase in a biological sample, and can be deployed for general and public use for high speed wireless communication.

5.2 Future Work

Current hyperthermia systems which utilize frequencies other than 60 GHz, operate at a power density which is lower than what is proposed in the model. It requires further investigation and experimentation to find precise dose-time combination so that high power density can be efficiently used for non-invasive hyperthermia at 60 GHz.

With the knowledge of the dielectric constant of water and biological samples at different frequencies, multiple samples can be tested or experimented using the proposed model.

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