CHAPTER 5

BASIC COMPUTER SIMULATIONS AND
PERFORMANCE PARAMETERS FOR MWA ANTENNA

5.1 Introduction

The simulative implementation of various MWA antennas designed in the present work has been done using the finite element method (FEM) based Comsol Multiphysics 3.4 (FEMLAB) software. It is a commercial software package, which solves partial differential equations using FEM, thus, the original boundary-value problem with an infinite number of degrees of freedom is discretized into a problem with a finite number of degrees of freedom.

The main feature of this software is that, it can be fully integrated with MATLAB. It also allows to design integrated models involving EM and thermal simulations resulting in highly accurate treatment of the complex coupled physical processes that occur during MWA. The fundamental coaxial antenna is considered in this chapter for performing descriptive analysis through finite element simulation.

5.2 Basic Modeling Procedure

Due to the cylindrical, axially symmetric nature of microwave coaxial antenna, the problem domain can be reduced to two dimensional domains and antenna is assumed to be immersed in a liver, which also exhibits cylindrical symmetry. All the EM and thermal models of this thesis work have been built in two dimensional axial-symmetrical mode because in 2D modeling, fine mesh can be selected to achieve excellent accuracy. In these conditions, the azimuthal dependency on the vector EM
field components and scalar thermal distribution can be accounted for analytically and factored out of the governing equations, while eliminating the need for gridding in the azimuthal direction. Thus, the antenna models have been created in 2D computational grids while preserving the full 3D nature of the vector EM fields. The 2D axially-symmetrical models are also called 2.5D models because model is computed in 2D, but represents the fields fully in 3D. Moreover it reduces the computation time from hours to seconds and improves grid resolution 10 times.

An EM waves involves both varying electric and magnetic field. The propagation of EM is described by differential form of complex time-harmonic steady state Maxwell equations 3.1-3.4. The Maxwell equations are basically partial differential equations, which proved that EM disturbances originated by a charged body can travel as a wave. These equations have brought together the various electrostatic and magnetic field laws in order to get the electric and magnetic field strength 3.20 – 3.40. The analysis of these equations not only predict the existence of EM waves but also predict the speed of propagation, depth of penetration, rate at which the energy is consumed using pointing vector 3.40 - 3.44. The knowledge of the dielectric properties of the tissue are also equally important as, because they are dependent on temperature and changes the tissue water and protein contents and at temperature greater than 60°C, the protein denaturization takes place and is irreversible. Gabriel suggested the empirical parameterized equation 3.47 to approximate the measured dielectric properties of different tissues.

When considering EM interaction with biological systems, it is important to distinguish between levels of fields outside the body and absorbed energy within the body tissue. This is usually quantified SAR, which is rate at which EM energy is
absorbed at a specific location and thus a good predictor of thermal effects equations 3.48-3.50.

SAR can be used to determine the increase in tissue temperature over a short period of time using bioheat equation 3.51. Moreover reliable techniques to quantify the thermal effect of the blood circulating in the arteries and veins are of equal importance and can be monitored by blood perfusion and effects 3.52.

The axial-symmetric models have some limitations also. They are better to represent a coaxial antenna in a simple homogeneous medium, but are not good enough to model medium with complex structures including large blood vessels. To deal such kind of problems 3D models are used instead of an axial-symmetric model but due to limited computational power for large 3D models, it often runs out of memory for large models, even when there is a significant amount of system memory available. Post-processing of data as well as its ability to integrate with MATLAB make it still the best choice for microwave ablation antenna models.

5.2.1 The basic EM model

The basic antenna model does not consider the changes of tissue dielectric properties due to the changes in tissue temperature and water content in the tissue during heating. The model therefore studies the antenna performance in static tissue dielectric properties. The model to be generated in COMSOL requires RF module and heat transfer module considering the harmonic propagation of transverse magnetic (TM) waves. The basic coaxial antenna geometry considered here is as shown in Figure 5.1 and the relevant geometrical dimensions of the antenna assembly are shown in Table 5.1 [239]. The antenna operates at 2.45 GHz, a frequency widely used in microwave coagulation therapy. The 2D axial geometry of the antenna is shown in Figure 5.2.
Table 5.1: Dimensions of antenna assembly

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter of the central conductor</td>
<td>0.29 mm</td>
</tr>
<tr>
<td>Inner diameter of the outer conductor</td>
<td>0.94 mm</td>
</tr>
<tr>
<td>Outer diameter of the outer conductor</td>
<td>1.19 mm</td>
</tr>
<tr>
<td>Diameter of catheter</td>
<td>1.79 mm</td>
</tr>
</tbody>
</table>

The antenna consists of a thin coaxial cable with a 1 mm wide ring shaped slot cut on the outer conductor 5 mm from the short-circuited tip. For hygienic purposes, the antenna is enclosed in a sleeve (catheter) made of PTFE (polytetrafluoroethylene a biocompatible dielectric material). The antenna is inserted in a volume of material with liver properties and is placed axisymmetrically with liver tissue. The external surface of the liver tissue acts as boundary for the computational domain.
5.2.2 Material Properties

Tables 5.2 and 5.3 summarize the electromagnetic properties and thermal properties respectively [239], required for implementing the antenna design through numerical simulation. The effective wavelength in liver tissue is approximately 19 mm (18.5 mm).

Table 5.2 Electromagnetic Properties at 2.45 GHz

<table>
<thead>
<tr>
<th>Name</th>
<th>Expression</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative permittivity, dielectric</td>
<td>eps_diel</td>
<td>2.03</td>
</tr>
<tr>
<td>Relative permittivity, catheter</td>
<td>eps_cat</td>
<td>2.6</td>
</tr>
<tr>
<td>Relative permittivity, liver</td>
<td>eps_liver</td>
<td>43.03</td>
</tr>
<tr>
<td>Electrical conductivity, liver</td>
<td>sig_liver</td>
<td>1.69 [S/m]</td>
</tr>
<tr>
<td>Relative permeability</td>
<td>εr</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 5.3 Thermal Properties for Analysis of Liver

<table>
<thead>
<tr>
<th>Expressions</th>
<th>Name</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Conductivity, liver</td>
<td>K_liver</td>
<td>0.56 [W/(kg*K)]</td>
</tr>
<tr>
<td>Density, blood</td>
<td>Rho_blood</td>
<td>1000 [kg/m^3]</td>
</tr>
<tr>
<td>Specific heat, liver</td>
<td>C_liver</td>
<td>3639 [J/(kg*K)]</td>
</tr>
<tr>
<td>Blood perfusion rate</td>
<td>Omega_blood</td>
<td>3.6 e-3 [1/s]</td>
</tr>
<tr>
<td>Blood Temperature</td>
<td>T_blood</td>
<td>37 [degC]</td>
</tr>
<tr>
<td>Specific heat, blood</td>
<td>C_blood</td>
<td>4810 [J/(kg*K)]</td>
</tr>
</tbody>
</table>

5.2.3 Domain and Boundary Equations-Electromagnetic Module

In axial-symmetric mode, there is no change in the azimuthal direction i.e the φ direction. The most users therefore select TM waves, as these waves have a magnetic
field with only a $\phi$ component and electric field in the $r$-$z$ plane. The fields can be written [258] as:

$$H(r, z, t) = H_\phi(r, z)e^{j\omega t}$$  (5.1)
$$E(r, z, t) = (E_r(r, z) + E_z(r, z))e^{j\omega t}$$  (5.2)

An electromagnetic wave propagating in a coaxial cable is characterized by transverse electromagnetic fields (TEM). Assuming time-harmonic fields with complex amplitudes containing the phase information, the appropriate equations are:

$$E = E_r \frac{c}{r} e^{j(\omega t - kr)}$$  (5.3)
$$H = E_\phi \frac{c}{rZ_i} e^{j(\omega t - kZ_i)}$$  (5.4)

$$P_{av} = \int_{r_{inner}}^{r_{outer}} \Re \left( \frac{1}{2} E \times H^* \right) 2\pi r dr = e_\epsilon \frac{c^2}{Z_i} \ln \left( \frac{r_{outer}}{r_{inner}} \right)$$  (5.5)

Where $z$ is the direction of propagation, $r$, $\phi$ and $z$ are cylindrical coordinates centered on the axis of the coaxial cable. $P_{av}$ is the time-averaged power flow in the cable, $c$ is the conductivity (S/m), $Z_i$ is the wave impedance in the dielectric of the cable, while $r_{inner}$ and $r_{outer}$ are the dielectric’s inner and outer radii, respectively. Further, $\omega$ denotes the angular frequency. The propagation constant, $k$, relates to the wavelength in the medium, $\lambda$, as

$$k = \frac{2\pi}{\lambda}$$  (5.6)

In the tissue, the electric field also has a finite axial component whereas the magnetic field is purely in the azimuthal direction. The wave equation then becomes scalar in $H_\phi$ as:

$$\nabla \times \left( \left( \frac{\varepsilon_r}{\varepsilon_0} \right)^{-1} \nabla \times H_\phi \right) - \mu_r \kappa_0^2 H_\phi = 0$$  (5.7)

The boundary conditions for the metallic surfaces are

$$n \times E = 0$$  (5.8)
The feed point is modeled using a port boundary condition with a power level set to 10 W. In this problem, a low reflecting boundary condition is set on the surfaces, so that boundary does not disturb the EMF distribution. The input field is given as:

\[ n \times \sqrt{\varepsilon}E - \sqrt{\mu}H_\phi = -2\sqrt{\mu}H_{\phi 0} \]  

(5.9)

Where

\[ H_{\phi 0} = \sqrt{\frac{P_{av}Z_{\phi}}{r \ln \left( \frac{\text{outer}}{\text{inner}} \right)}} \]  

(5.10)

for an input power of \( P_{av} \) deduced from the time-average power flow.

The antenna radiates into the tissue where a damped wave propagates. Because one can discretize only a finite region, must truncate the geometry at some distance from the antenna using a similar absorbing boundary condition without excitation. The boundary conditions can be applied to all exterior boundaries. Finally, symmetry boundary conditions for boundaries at \( r = 0 \) are applied.

### 5.2.4 Domain and Boundary Equations-Heat Transfer

The bioheat equation describes the stationary heat transfer problem as [258]:

\[ \nabla \cdot (-k \nabla T) = \rho_b C_b \omega_b (T_b - T) + Q_{\text{met}} + Q_{\text{ext}} \]  

(5.11)

where \( k \) is the liver’s thermal conductivity (W/(m·K)), \( \rho_b \) represents the blood density (kg/m\(^3\)), \( C_b \) is the blood’s specific heat capacity (J/(kg·K)), and \( \omega_b \) denotes the blood perfusion rate (1/s). Further, \( Q_{\text{met}} \) is the heat source from metabolism, and \( Q_{\text{ext}} \) is an external heat source, both measured in W/m\(^3\).

This model neglects the heat source from metabolism. The external heat source is equal to the resistive heat generated by the electromagnetic field:

\[ Q_{\text{ext}} = \frac{1}{2} \text{Re}[(\sigma - j\varepsilon)E \cdot E^*] \]  

(5.12)
The model assumes that the blood perfusion rate is $\omega_b = 0.0036 \text{ s}^{-1}$, and that the blood enters the liver at the body temperature $T_b = 37 \degree C$ and is heated to a temperature, $T$. The blood’s specific heat capacity is $C_b = 3639 \text{ J/(kg·K)}$.

This model deals with the heat-transfer problem only in the liver domain. It is assumed that in the heat transfer problem the boundary is thermally isolated. Where the liver domain is truncated, it uses insulation, that is

$$n \cdot \nabla T = 0 \quad (5.13)$$

5.2.5 Meshing

In order to achieve best accuracy it is always better to use fine mesh elements. The size of mesh elements must be selected so that the solution converges and provide enough accuracy. Generally it is common practice to use mesh element size at 1/10 to 1/8 of the wavelength. At the frequency at 2.45 GHz, the wavelength in liver tissue is about 18.6 mm, hence meshing element size is usually set to 2.3 mm, which is slightly smaller than 1/8 of the wavelength.

![Figure 5.3 Meshing of coaxial antenna model](image)

This mesh element size gives the solution with enough accuracy within reasonable computation time. Because if too fine mesh elements are used, they increase the computational time without further increasing the computation accuracy. Figure 5.3 shows the fine mesh obtained for the computational domain before solving the model.
5.2.6 Results

To solve 2D axisymmetric model, 180MB memory and approximately 50s of CPU time is required for each simulation on an Intel P5, 2.66GHz computer. Direct unsymmetric sparse linear systems (UMFPACK) solver has been used to solve the model because it is a highly efficient direct solver for unsymmetric systems. After solving the EM model, the obtained solution can be analyzed by plotting graphs for all field variables using the postprocessing features in COMSOL Multiphysics.

The boundary and volume integrations for the field variables can also be performed to calculate power delivered, reflected, deposited and leaked. The total power deposited is calculated by volume integration of SAR in the liver tissue, and the power leaked from the external boundaries of liver tissue.

The power leaked at a boundary is calculated by the boundary integration of the normal vector of the power flow vector on the boundary, and the total power delivered by the power source is calculated at the power source boundary by the boundary integration of the normal vector of the power flow vector. Hence total reflected power is calculated by subtracting the total delivered power from the input power.

After calculating the reflected power, power reflection coefficient $\Gamma$ for the antenna can be calculated at the operating frequency.

\[ P_{\text{deposited}} = P_{\text{absorbed}} + P_{\text{leaked}} \]  
\[ P_{\text{in}} = P_{\text{delivered}} + P_{\text{reflected}} \]  
\[ \Gamma = \frac{P_{\text{in}} - P_{\text{delivered}}}{P_{\text{in}}} \]

5.2.6.1 Computation of Antenna Frequency Response with MATLAB

After determining the antenna power reflection coefficient $\Gamma$, the spectrum of $\Gamma$ can be computed at discrete frequencies from 0 GHz to 10 GHz. The advantage of integration of COMSOL and MATLAB has been taken into account for the
computation of frequency response of the antenna. The antenna model was saved from COMSOL into a MATLAB script file. The MATLAB script is the sequential MATLAB functions which can be called into COMSOL for the whole EM model, including geometry, boundary/domain parameter setting, meshing, problem solving and post-processing results.

The MATLAB script which is able to accept frequency-dependent input parameters computes the model at a single frequency and calculate the antenna power reflection coefficient at the particular frequency. Finally it generates the complete plot at different frequencies for the antenna power reflection spectrum.

5.3 Performance Parameters of MWA Antenna

An antenna is an electrical component which can radiate the energy to the targeted tissue. The antenna's performance, in general, is characterized by some basic terms, such as temperature distribution and thermal lesion, antenna efficiency, reflection coefficient $S_{11}$, SAR and power deposition [257]. In this section, these parameters are introduced and further evaluated for the simulated coaxial antenna.

5.3.1 Temperature Distribution and Thermal Lesion

The thermal lesion is defined as the distribution of the microwave heat source, and the temperature field follows the heat-source distribution quite well as shown in Figure 5.4. The thermal lesion is strong near the antenna heat source, which denotes high temperatures, while far from the antenna, the heat source is weaker and the blood manages to keep the tissue at normal body temperature. The predicted ablation zone calculated from an FEM model helps the physicians to determine optimal trajectories for inserting the applicator. Hence some studies consider a simplified FEM model which reduces the computation time, at the cost of accuracy.
Figure 5.4: (a) Temperature plot and (b) Surface heat plot

5.3.2 Reflection Coefficient ($S_{11}$)

The efficiency of an antenna may be depicted by the reflection coefficient $S_{11}$, which can be expressed logarithmically as in equation 5.17. The frequency, at which the reflection coefficient is minimum, is referred to as the resonant frequency and should be approximately the same as the operating frequency of the microwave generator used. Antennas operating with high reflection coefficients (especially at higher power levels) can cause overheating of the feed line, possibly leading to damage of the coaxial line or of the tissue due to the thin outer conductor.

$$S_{11} = -10 \log_{10} \frac{P_r}{P_{in}} \quad [\text{dB}]$$

(5.17)

The reflection coefficient obtained in the frequency range of 0-10 GHz is -18 dB at the resonant frequency of 2.45 GHz.
5.3.3 Specific Absorption Rate (SAR)

SAR can be determined from measurements of increase in the tissue temperature over a short period of time following the exposure. SAR determination is based upon the thermal measurements and utilization of equations described in chapter 3. More generally, from a macroscopic point of view, thermal effects resulting from the absorption of EM waves inside biological materials are described in terms of the bioheat equation. The Figure 5.5 shows the SAR obtained which depicts the localized power at the antenna tip.

![Figure 5.5 Specific Absorption Rate (SAR) plot](image)

5.3.4 Antenna Size

The heating is performed through the use of thin interstitial antennas that radiate electromagnetic power at microwave frequencies, usually 915 MHz or 2.45 GHz. The microwave antenna is inserted into a insertion device, which surrounds and protects the antenna during the placement into the targeted deep seated tissue, and, when the antenna has been positioned into right place, the insertion device is retrieved back.
Hence the antenna should be of miniaturized size and must have the sufficient strength so that during insertion it must not get mechanically damaged, when repositioned.

5.3.5 Power Deposition

The total heating power deposited in the liver tissue is computed by volume integration of resistive heating, time average in the liver domain. The calculated value of power in watt indicates the amount of power absorbed in the liver at stationary conditions. The obtained power deposition value is approximately 9.37 W which indicates that the tissue absorbs most of the 10 W input power at stationary conditions.

5.4 Objectives for Assessing Antenna Performance

After computing the temperature profiles using FEM model, the lesion size, shape, and antenna efficiency are used to assess antenna performance. Since most of the HCC tumors are spherical in shape [259], the major goal is to optimize the antenna to yield the spherical lesion with larger radius. Two metrics have been identified to access the size and shape of the lesion: a) lesion radius and b) axial ratio. These metrics are shown in Figure 5.6 with an example of ablation profile.

The radius of ablation zone is defined as maximum extent of ablation zone in radial direction. The axial ratio is defined as ratio of radius of ablation to the width of the ablation zone, note that this ratio must fit to 0.5, as it yields spherical lesion shape.

The most commonly quoted parameter in regards to antenna performance is $S_{11}$. It represents how much power is reflected from the antenna, and hence is known as the reflection coefficient or return loss $\Gamma$. If $S_{11}=0$ dB, then all the power is reflected from the antenna and nothing is radiated. Since the antenna, to be optimized is used for percutaneous procedure; it is desirable to yield antenna design, meeting out objective metrics as shown in Table 5.5.
Table 5.4: Objective Metrics

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Metric objective</th>
<th>Means to measure</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Lesion radius</td>
<td>Size of lesion in radial direction</td>
<td>Maximum</td>
</tr>
<tr>
<td>2.</td>
<td>Axial ratio</td>
<td>Proximity of lesion shape to sphere</td>
<td>Fit to 0.5</td>
</tr>
<tr>
<td>3.</td>
<td>S11</td>
<td>Efficiency of antenna</td>
<td>Minimum</td>
</tr>
<tr>
<td>4.</td>
<td>Probe radius</td>
<td>Radial size</td>
<td>Minimum</td>
</tr>
</tbody>
</table>

5.5 Conclusions

Microwave ablation is one of the thermal ablation mechanisms capable of creating large ablation zones in shorter treatment times. For this purpose, the microwave irradiation power (in watts) must be sufficiently high and the antenna must be able to withstand this power. Computational models predicting thermal profiles and tissue damage play a substantial role in the development and understanding of antennas used for MWA. Microwave antennas being the integral part of treatment planning tools, helps the physicians to perform ablation procedures by determining the parameters such as optimal antenna placements, power levels and treatment durations for individual patients.

In this chapter computer simulations of basic coaxial antenna used for MWA has been performed using COMSOL Multiphysics. The performance evaluation of the antenna has been further done by determining the parameters like temperature field,
thermal ablation, specific absorption rate (SAR), reflection coefficient $S_{11}$, antenna size, power deposition etc. In addition the objective matrices have also been identified based on which antenna design is optimized to yield the complete tumor ablation.