RF Applicator Design for Efficient Heating of Materials

F. Jeni Anto and Dr.A. Sumathi

Abstract---Conventional heating of material wastes energy during heating due to inherent radiation, conduction and convection based heating mechanism. Alternate efficient heating methods are actively researched for improved efficiency and quality. Radio frequency based electromagnetic heating is increasingly used for efficient heating in place of conventional radiation based heating.. The radio frequency based heating, which requires coupling of electromagnetic and heat transfer for performance evaluation is used for design of an RF electromagnetic applicator. A dielectric disk is considered for heating performance evaluation. The methodology, material properties used and simulation results are reported. The uniformity of heat application or electromagnetic energy distribution is used as metric to evaluate the efficiency of the RF heating applicator. The virtual design and heating results and comparison with experiments are reported. The metaphysics coupling and parametric modeling capability of COMSOL for optimal design of applicator are highlighted.

Keywords---Heating, RF Heating, Electromagnetic Heating, Dielectric Heating, Coupled Heat Transfer, Uniform Heating

I. INTRODUCTION

RF based Electromagnetic heating method provides opportunity for efficient heating of materials and improved quality [1-5]. The energy and cost efficient designs are required as a competitive differentiator for new product and process development. Electromagnetic heating provides an alternative to conventional radiation based heating. This paper details about an RF applicator design for electromagnetic heating of dielectric disk. The coupled electromagnetic heat transfer formulation methodology and implementation of the model in COMSOL is given. An analytical formulation was also developed to predict the overall performance and is compared with COMSOL simulations. The overall design methodologies and simulation results are reported. A special focus is given to the applicator design for uniform field and hence heating. The inside out heating performance of RF heating compared to conventional outside in heating is highlighted by comparing the power uniformity index. The numerical Design of Experiments (DoE) related to applicator design is detailed. The parameters contributing to the uniformity is highlighted and calibrated against the physical fabrication limitation. The optimal and finalized configuration and the results are also reported.

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II. 2.0 GOVERNING EQUATIONS

The following two Maxwell equations govern the interaction of electromagnetic field with material properties and relate the time variations of one field to spatial variation of the other [1-5].

$$\overline{\nabla} \times \overline{H} = \sigma \overline{E} + \varepsilon \frac{\partial \overline{E}}{\partial t}$$

$$\overline{\nabla} \times \overline{E} = -\mu \frac{\partial \overline{H}}{\partial t}$$

Where,

$\overline{E}$, electric field vector,

$\overline{H}$, magnetic field vector,

σ, conductivity,

ε, permittivity,

μ, permeability.

The applicator design in the RF frequency range can be modeled using sinusoidal time varying steady state governing equations, due the electrically small size of the applicator, as follows,

$$\overline{\nabla} \times \overline{H} = \sigma \overline{E} + j\omega\varepsilon \overline{E}$$

$$\overline{\nabla} \times \overline{E} = -j\omega\mu \overline{H}$$

Where,

ω, is the angular frequency,

j, is the complex operator.

The radio frequency interaction with material for heating is related to the permittivity of the material. The complex relative permittivity comprises a real part which is responsible for phase shift and the imaginary part which is responsible for the energy loss, as follows,

$$\varepsilon_r = \varepsilon_r' - j\varepsilon_r''$$

Where,

ε_r' is the relative permittivity or dielectric constant and

ε_r'' is the loss or dissipation factor.

The governing equation relating the current density to the material properties can be written as follows,

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$$\bar{J} = (\sigma + \varepsilon_0\, \varepsilon_r''\, \omega)\bar{E} + j\, \varepsilon_0\, \varepsilon_r'\, \bar{E}$$

Where,

$\bar{J}$, Current density

The dielectric loss component of interest to RF heating can be written as follows,

$$\bar{J} = \varepsilon_0\, \varepsilon_r''\, \omega \bar{E}$$

The power dissipation factor per unit volume (Pv) in W/m3 for dielectric loss effect is,

$$P_v = \varepsilon_0\, \varepsilon_r''\, \omega E^2$$

This equation can be used to estimate the overall volumetric behavior and limiting design parameters.

The heating of materials is governed by the Fourier heat transfer equation, as follows,

$$\rho C_p \frac{\partial T}{\partial t} + \nabla(-k \nabla T) = P_v$$

Where,

ρ, is the density,

C_p, is the specific heat,

k, is the thermal conductivity, and

T, is the temperature.

The volumetric temperatures rise (dT) due to the power deposited into the material can be calculated as follows,

$$\Delta T = \frac{P_v t}{M_a C_p}$$

Where,

Ma, is the mass, and

t is the time.

The above equation assumes that the whole electrical energy is converted into thermal energy and there are no heat and other losses. The coupled electro thermal numerical model will provide us the predictive capability for realistic potential distribution, power density and temperature. The analytical and numerical formulation and results are used for performance comparison.

III. SIMULATION METHODOLOGY

COMSOL Multiphysics was selected for electrical, thermal and coupled electro thermal simulation. The AC/DC module was used for estimating the power uniformity index and optimization of electrode. The microwave heating module was used for estimating the temperature distribution. The readers are referred to the COMSOL theory manual for further details related to the theory and implementation of coupled electromagnetic and thermal simulation

A parametric CAD model of the dielectric heating applicator and the heating enclosure was developed. This is used for estimating the overall performance. For electrical field potential distribution, the AC/DC module was used. Obtaining uniform power distribution, i.e., the power uniformity is a critical challenge and hence a method to estimate the power uniformity index (PUI) is implemented in COMSOL. The importance is given to the PUI estimation.

The Equation for PUI is given as

$$\text{PUI}=\frac{\frac{1}{V_{vol}}\left(\int_{V_{vol}} \sqrt{((P-P_{av})^2)}\right)dV}{P_{av}}$$

Where $V_{vol}$the Volume of the sample is, P is the local power dissipation density. It is given as $P = 2\pi f \varepsilon_0 \varepsilon'' |E|^2$, where f is the frequency of input signal, ε_0 is the vacuum permittivity, ε'' is the imaginary part of the relative permittivity of the sample (Dissipation factor), and E is the electric field strength. The unit of this term is W/m^3. P_{av} is the Average Power Dissipation. It is calculated from the formula

$$P_{av} = \frac{1}{V_{vol}} \int_{V_{vol}} P dV$$

We used parametric model, probe variable and derived values of COMSOL Multiphysics for predicting the PUI as function of optimization parameters. From the above equations, it is clear that PUI refers to the uniformity of electric field power distribution. It is understood that PUI should be smaller for better RF power uniformity in the dielectric material. The objective function of optimisation was to minimise the PUI as function of design variables such as electrode size, distance, electrode shape. This DOE helped us to locate the best design parameters of the applicator for lowest PUI.

The parametric model enabled to perform sweeps to explore the overall trend. A detailed analysis was then performed for the final selected results. The effects of electrode distance, size, shape, air volume, sample distance from the electrode are parameterized for the design of experiments. The dielectric sample size was fixed at constant size of 50 mm diameter and 4 mm thickness.

The simulation Methodology and steps are summarized as follows,

- Preprocessing of the CAD model of the sample, electrodes and air volume.
- Define Materials and find capacitance of the structure using COMSOL. Then numerically benchmarking the COMSOL prediction with analytical.
- DoE of electrode configuration, distance, dielectric disk size and shape.
- Optimization of structure for lowest power uniformity.

The dielectric properties (Dielectric constant and loss factor) of the disk are shown in table 1. Further, specific heat capacity of 2059 J/Kg C, and density of 1541 kg/m3 is considered. In addition a range of properties are also used for estimation of bounds for DoE. The temperature dependent material property models are also used as appropriate to factor the thermal rise.

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TABLE 1
TYPICAL MATERIAL PROPERTIES USED FOR SIMULATION.

Material	□'	□''
Air	1.0006	0
Water (20oC)	80.4	3.216
Water (100oC)	55.3	8.5162
Dielectric Disk	6.47	0.97

IV. RESULTS AND DISCUSSION

This section provides the critical observation and results related to the applicator design for uniform heating of dielectric disk. The DoE results, predictive performance of the applicator electrode, optimized electrode geometry are detailed. The PUI and heating results are shown in Figure 1-4. Figure 1 and 2 shows the Power uniformity optimization results. Figure 3 and 4 shows the RF heating performance as function of dielectric properties of the disk.

The size of electrode was changed from 30 mm to 100 mm diameter and results are as shown in figure , for a electrode gap distance of 10 mm. The PUI was lower around the diameter of the dielectric disk and is lowest at around 48 mm. This is comparable to the size of the sample. An electrode size of 46 to 50 mm will provide us PUI of less than 0.1. The electrical field and field strength distribution is at the lowest PUI is shown in figure 1. Further the sample distance between the electrodes was investigated and the sample at the center provided the lowest PUI.

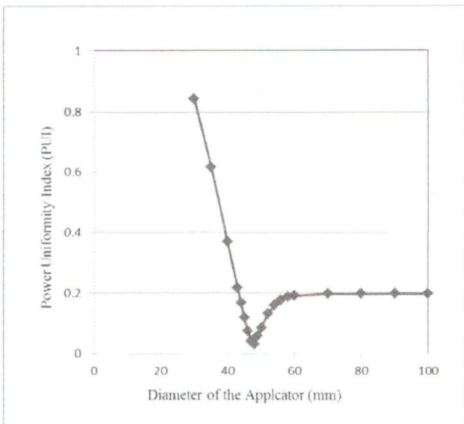

Fig 1 Power Uniformity Index as a Function of the Diameter of the Applicator

Another DoE was performed on a larger electrode with an angle between top and bottom surface. An electrode diameter of 100 mm is considered with lower internal diameter as function of angle. The results are shown in figure 2. The lowest PUI was observed at at around 80 degree.

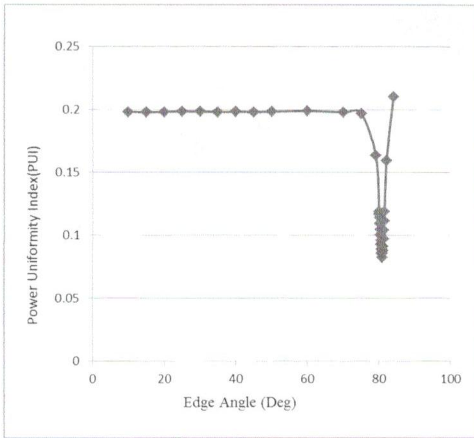

Fig 2 Power Uniformity Index as a Function of the Edge Angle of the Applicator

An investigation performed to study the effect of material properties on the heat up performance using the microwave-heating module. The sample dielectric constant and loss factor varied from 6.5 to 15 and 1 to 10, respectively. The increase in dielectric constant and loss factor increases the heat buildup. The loss factor plays a significant role in the heat buildup. This simulation is study the effect of material property on the performance. The temperature contour plots are shown in figure 3 and 4.

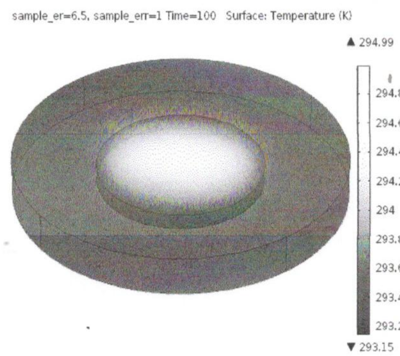

Fig 3 Typical Coupled Electro Thermal Results and Temperature Distribution for Dielectric Constant of 6.5 and Loss Factor 1

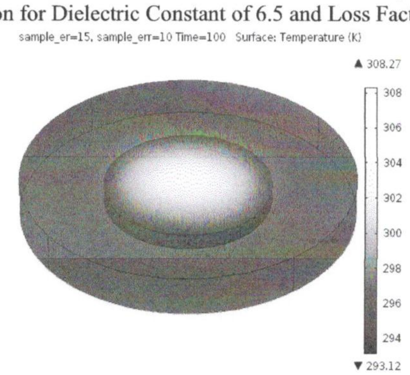

Fig 4 Typical Coupled Electro Thermal Results and Temperature Distribution for Dielectric Constant of 15 and Loss Factor 10

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