Particularities of the Dielectric Heating in RF. Applicator Optimization

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Abstract: This paper presents a quality analysis of the electromagnetic and thermal field coupling in Radio-Frequency (RF) dielectric heating, neglecting the mass problem. Also it presents numerical modeling results of one piece wood board heating disposed into a staggered-through field applicator. Studying the specialty literature the authors haven’t found any detailed study concerning the optimisation geometry of this type of applicator for a given application where the dimensions and dielectric properties of heating material are known. The software used was Flux2D-7.40 with Dielectric-Thermal module. At the end we offer essential results, such as the optimization of the voltage on the electrodes and also the applicator geometry, for some users of electrothermal processing in RF.

Key words: RF electromagnetic field, Thermal field diffusion, Numerical modeling, Staggered-Through field applicator, 2D structure

I. ELECTROMAGNETIC FIELD EQUATIONS

The RF heating suppose the non-magnetic quasi-static electromagnetic field [1], where time derivation of magnetic induction is neglected. Considering the harmonic regime, we can use the complex images and the electromagnetic field equations are

\[ \mathbf{E} = - \text{grad} \mathbf{V} \]
\[ \text{rot} \mathbf{H} = \mathbf{J} + j \omega \mathbf{D} \] (1)
\[ \mathbf{D} = \varepsilon \mathbf{E} \]
\[ \mathbf{J} = \sigma \mathbf{E} \]

In D-E relationship, we consider the complex permittivity

\[ \varepsilon = \varepsilon' - j \varepsilon'' \] (2)

which takes into account the dielectric losses.

The potential equation for nonconductive materials is

\[ \text{div} \varepsilon \text{grad} \mathbf{V} = 0 \] (3)

The power losses in dielectric are

\[ p = \omega \varepsilon' \mathbf{E}^2 \] (4)

II. THERMAL FIELD DIFUSSION

The Fourier equation for steady state of thermal field is

\[ -\text{div} \lambda \text{grad} T = p \] (5)

where \( \lambda \) represents thermal conductivity, and \( p \) represents power density, which is transformed from electromagnetic form into heat (4).

The boundary condition is

\[ -\lambda \frac{\partial T}{\partial n} = \alpha (T - T_e) \] (6)

where \( \alpha \) is the convection heat transfer coefficient and \( T_e \) represents the temperature outside the charge.

The heat diffusion equation is given by

\[ -\text{div} \lambda \text{grad} T + c \frac{\partial T}{\partial t} = p \] (7)

where \( c \) is the specific volume heat \( T_0 \) to (7) we add the boundary condition (6), and the initial condition for temperature: \( T(0) = T_{in} \).
III. NUMERICAL APPLICATION OF RF DIELECTRIC HEATING

The Staggered-Through field applicator is used at greater thickness dielectrics (plywood, boards) heating. The physical model analysed consists of an applicator with 8 cylindrical electrodes disposed in two rows with 4 pairs, Figure 1. Horizontally, each one of two consecutive electrodes is supplied at same potential. Vertically, the two electrodes disposed oblique have different potential.

The interior of circles which are the applicator electrodes is out from electrical field calculation domain.

Because the majority of materials have dielectric and thermic properties depending on temperature, the solving of the problem takes account by the electric and thermal field coupling, meaning that in the same time with the temperature variation also the heated material dielectric properties are modified, so is modified the electrical field distribution inside of it.

In Figure 2 are presented the 2D structure of the electric and thermal field domain.

The initial and boundary condition are:

- For electrical field
  - homogeneous Neumann condition, \( \nabla V / \nabla n = 0 \), on the ABCDEFGH border;
  - Dirichlet boundary condition on electrodes:
    \( V = U \) on (1) and (3) - U is the applicator effective voltage supply;
    \( V = 0 \) on (2) and (4);

- For thermal field
  - thermic transfer through convection boundary condition on HC and GD
    \( -\lambda \cdot \nabla T / \nabla n = \alpha \cdot (T - T_e) \) where \( \alpha \) is the convection heat transfer coefficient and \( T_e \) represents the temperature outside the charge
  - zero thermal flux condition, \( \nabla T / \nabla n = 0 \), on GH and DC border (homogeneous Neumann condition). Strictly, it should imposed a periodically condition, but the small thickness of the charge justifies the Neumann condition approximation.

Parameters are:

- working frequency \( f = 13.56 \text{ MHz} \)
- voltage on electrode \( U = 1800 \text{ V} \)
- voltage on other electrode \( U = 0 \text{ V} \)
- initial temperature \( 20^\circ \text{C} \)

As dielectric we consider one piece of wood board with 30% moisture, 10 mm thickness.

The dielectric properties at \( 10^7 \text{ Hz} \) \cite{3}, \cite{4} ar

\[ \varepsilon' = 4.1 \text{ and } \tan \delta = 0.219 \]

Thermic properties

\[ \lambda = 0.1 \text{ [W/m}\cdot\text{0C}] \]
\[ \rho = 800 \text{ [kg/m}^3\text{]} \]
\[ c_s = 800 \text{ [J/kg}\cdot\text{0C}] \]
\[ \alpha = 15 \text{ [W/m}^2\cdot\text{0C}] \]

In the following part a study method is illustrated, that optimize the electrodes voltage \( U_{cor} \) (the heating temperature was limited at \( 100^\circ \text{C} \) to not deteriorate the board).
depending on the heating report,  
\[ k = \frac{T_{\text{max}} - T_{\text{min}}}{T_{\text{max}}} \]  
(8)

(where \( T_{\text{max}} \), \( T_{\text{min}} \) are the maximum, respectively the minimum heating board temperature) and depending on the distance between two opposite electrodes, for different geometrical parameters. We used the Flux2D software for the optimization. Also, we followed the k variation depending on the distance between electrodes.

IV. NUMERICAL RESULTS WITH FLUX2D

Flux2D is a package CAD for the thermic and electromagnetic analysis with finite elements and uses the triangles method for the calculation domain discretisation. This method allows the creation of the iterative triangles through the insertion, in the discretisation network, one by one, of the existing junctions between points and lines and then of the junctions on the surface.

The Dielectro-thermal module of the software Flux2D allows the numerical analysis of the potential (voltage) and the electromagnetic field distribution in devices including the nonperfect dielectrics that support sinusoidal voltage.

The dielectrothermal application allows to deal with coupled problems, by taking into account the power dissipation in the dielectric by Joule’s effect, and the dependencies of the conductivity versus the temperature [2].

Also it calculates simultaneously the electric and thermal field equations.

The dielectric equation is
\[ \text{div} \left[ \frac{1}{\rho(T) + j \omega \varepsilon'} \right] \cdot \text{grad}V = 0 \]  
(9)

The thermal equation is
\[ \lambda \Delta T + \rho C_p \frac{\partial T}{\partial t} = P_j \]  
(10)

\( P_j \) is the power dissipated by Joule’s effect
\[ \rho I^2 = \frac{V^2}{\rho} \]  
(11)

The properties are described by \( \varepsilon’ \) and \( \varepsilon'' \), or tan \( \delta \), with the following meaning
\[ \varepsilon’ = \varepsilon_0 \cdot \varepsilon_r \]  
(12)

where \( \varepsilon_r \) is the relative permittivity of the material and \( \varepsilon_0 \) is the permittivity of vacuum
\[ \tan \delta = \frac{\varepsilon''}{\varepsilon'} \]  
(13)

where \( \delta \) is the “angle of dielectric losses”.

The equivalent resistivity used in Flux2D is:
\[ \rho = \frac{1}{\sigma} = \frac{1}{\omega \varepsilon' \tan \delta} \]  
(14)

This value includes the angular velocity \( \omega \), and is not an intrinsic property of the material, but an equivalent property which takes into account several phenomena depending generally on the voltage frequency and the dielectric field. Figure 3 shows the FLUX-2D calculation domain.

Because we are not interesting by the real power dissipation in charge, the calculation domain is reduced at the space between two consecutive opposite electrodes (1 and 2).

The geometry was initiated considering that \( \Delta, \phi \) and \( h \) are parametrized.
- \( \Delta \) - horizontally distance between two opposite electrodes;
- \( \phi \) - electrodes diameter;
- h - vertically distance between two opposite electrodes.

The constant parameters are - ε, tgδ and the thickness of board g =10 mm.

The calculation domain depth for volumetric integration measures was considered 1800 mm.

It was done about 183 computations. One by one parameter was kept constant, and the others two were variated. The initial electrodes voltage was chosen arbitrary. The geometric parameters were used like laboratory model, and it can be extended at the industrial applications.

The expression of corrected voltage, \( U_{cor} \) is:

\[
U_{cor} = \frac{100}{\sqrt{T_{max}}} \quad (15)
\]

In Figure 4 are presented corrected voltages values variation vs. distance between electrodes for each values of h (14, 16 and 12) considering electrode diameter \( \phi = 10 \), and in Figure 5 are presented the ratio heating vs. distance between electrodes in same conditions. It can be observe the increasing of voltage value during the distance between electrodes increasing as well as heating ratio increasing upon electrodes approaching.

V. CONCLUSIONS

After many computations, it was observed the temperature differences results. Therefore we optimise the input electrodes voltage also for geometrical applicator parameters to limit superior the value of temperature.

As we observe the heating may be consider uniform, the difference between „hot” and „cold” points are small. Therefore it no use to move the load through applicator.
Also, in studied geometry, the heating temperatures are situated in the accepted limits of wood processing.

REFERENCES


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