COMPUTATIONAL TOOLS FOR SYNTHESIS OF A MICROWAVE HEATING PROCESS RESULTING IN THE UNIFORM TEMPERATURE FIELD

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Abstract
This paper provides a general description of the analysis and synthesis computational tools of the modeling-based technique for solving the fundamental problem of intrinsic non-uniform microwave heating. First piece of the software implements an FDTD solution of a coupled electromagnetic-thermal problem with varying parameters and pulsing microwave energy. This tool allows for choosing the design variables for the optimization problem which is formulated as minimization of time-to-uniformity and solved by the synthesis software producing a description of the optimal heating process with the resulting uniform 3D temperature field. A novel temperature-based measure for the uniformity of microwave-induced temperature patterns is introduced as the average squared temperature deviation corresponding to all distinct neighboring pairs of FDTD cells in the load.

INTRODUCTION
The traditional approach for improving microwave (MW) heating systems has been experimentation. However, given the continually expanding capabilities of hard- and software, an alternative approach that has recently gained certain popularity is computer modeling [1, 2]. The increasing demand for general-purpose multi-physical modeling software has resulted in the development of several advanced modeling tools. A number of commercial products currently exist which are capable of effectively simulating the electromagnetic component of MW heating [2]; a number of recent studies (e.g., [3-5]) report on successful modeling in the framework of numerical procedures coupling the electromagnetic (EM) and thermal (T) processes.

Although these advanced modeling tools may be capable of quite adequate analysis of systems of MW thermal processing, they do not provide direct recommendations for practical design in terms of how the intrinsic non-uniformity of MW heating could be overcome. Moreover, a literature analysis indicates that there is no generally established criterion for measuring uniformity of MW-induced temperature fields. While some researchers believe that the temperature field can be homogenized by evening up the pattern of the electric field [6-10], other authors quantify the level of uniformity of MW heating through the spatial distribution of dissipated power [11, 12]. As a result, there is no commonly accepted formulation for the corresponding optimization problem.

This paper is concerned with the problem of synthesis of the MW heating process resulting in the desirable, specifically uniform, heating pattern. We provide here a general description of the modeling and optimization computational tools being two elements of the general modeling-based technique for solving the problem of non-uniform MW heating. This technique introduced in [13] is based on a finite-difference time-domain (FDTD) solution of a coupled EM-T problem and relies on heat diffusion as a vital mechanism in achieving uniformity of heating. Here, we bring in a novel temperature-based measure for the uniformity of MW-induced temperature fields, formulate the optimization problem and outline a procedure for its solution. Both pieces of software are implemented within the MATLAB environment and call, when necessary, the components of the 3D conformal FDTD electromagnetic package QuickWave-3D (QW-3D) (www.qwed.com.pl) including the QW Basic Heating Module (QW-BHM) and the QW Heat Flow Module (QW-HFM) responsible for updating temperature and material parameters, and solving the heat transfer problem, respectively.

MODELING TOOLS
Aiming to improve heating uniformity and considering a related modeling-based optimization, one should decide on which general parameters of the system are suitable for being design variables. It is
known from experimentation and modeling that significant changes in the heating pattern can be obtained by modifying the design parameters of MW systems. We also consider using the mechanism of heat diffusion to improve the uniformity of the temperature field since it effectively relaxes hot and cold spots [13]. We thus introduce the concept of pulsed MW heating with variable characteristics and use this idea as a source for formulating a suitable optimization problem and its solution.

In the developed algorithm, the total heating time is partitioned into a series of time steps. Then, each time step is partitioned into two sub-time steps in which MW heating is simulated in the first sub-time step, but only thermal relaxation is simulated in the second one. This is accomplished by solving the EM portion of the problem using the current material parameters and by solving the T portion (using the computed electric field as the source in the thermal model) over the entire heating time step, whereas the source term in the thermal equation only accounts for application of MW power during the first sub-time step. After the T problem is solved, material parameters are upgraded based on the new temperature field.

Based on the described solution algorithm, pulsing has been incorporated into the QW-3D/QW-BHM implementation of the EM-T solution algorithm by using a batch file to control the \texttt{hfm.exe} file which solves the T portion of the problem. The next step is to accurately and efficiently simulate complex MW scenarios in which design parameters change over the course of time. However, the parameters of interest (ones that determine the MW system) cannot be changed during the normal operation of the QW-3D software. From the analysis of the structure and operation principles of QW-BHM, we found it possible to simulate MW heating experiments by managing the *.hfi file that is produced by \texttt{hfm.exe}. We are able to reload the saved fields described within this *.hfi file back into the QW-Simulator core by further modifications of the developed batch file (Fig. 1).

**OPTIMIZATION TOOLS**

The unique step-by-step description of a given MW heating process in terms of the modification of model parameters as a function of time is defined as the corresponding operating procedure. Using the concepts of time-to-uniformity [13] and operating procedure, we mathematically define the optimization problem as follows: given a specific MW heating system and load configuration, find the operating procedure $P^* \in \Omega$ which satisfies

$$ t_u(P^*) = \min_{P \in \Omega} t_u(P), $$

(1)

where $\Omega$ is the set of all operating procedures $P$ which satisfy

$$ T_M(t,P) \leq T_{\text{MAX}} \text{ for all } t > 0. $$

(2)
In this situation, an operating procedure is reduced to the unique description of a MW heating process in terms of the time-specific modifications of chosen design variables. Moreover, the entire optimization problem can be alternatively formulated as the minimization of time-to-uniformity [13].

The optimization algorithm proceeds at each heating step by choosing, among all tested configurations, the set of values of design variables which produce the most uniform heating pattern. The temperature field that results from using this optimal set of parameters is then saved and used as the basis for the next heating step, as illustrated in Fig. 2. The tested model configurations used in the optimization procedure are chosen based on the idea of complementary heating patterns. The optimization is performed using each heating step as a constant predefined number, except when the maximum temperature exceeds the prescribed threshold $T_{\text{MAX}}$. In this case, the heating time is reduced so that the maximum temperature equals the threshold. Pulsing MW power is supposed to back up the process in order to let heat diffusion reach the cold spots not addressed by the MW heating controlled by the design variables.

In the absence of a commonly accepted standard definition for the uniformity of MW-induced temperature fields, in this paper, uniformity is measured as the average squared temperature deviation corresponding to all neighboring pairs of FDTD cells which represent the heated material:

$$U = \frac{1}{N} \sum_{i=1}^{N} (T_i^{(1)} - T_i^{(2)})^2$$

where each $(T_i^{(1)}, T_i^{(2)})$ represents the temperature values corresponding to the $i$th distinct pair of adjacent FDTD cells (Fig. 3), and $N$ is the total number of distinct pairs.

The method used to compute this sum relies on the structure of the FDTD mesh. For every set of adjacent cells in a chosen direction, we compute the contribution by expanding the corresponding terms from the total sum:

$$\sum_{i=1}^{n} (T_i^{(1)} - T_i^{(2)})^2 = \begin{bmatrix} T_1^{(1)} & T_2^{(1)} & \cdots & T_n^{(1)} \\ T_1^{(2)} & T_2^{(2)} & \cdots & T_n^{(2)} \end{bmatrix}^T \begin{bmatrix} T_1^{(1)} \\ T_2^{(1)} \\ \vdots \\ T_n^{(1)} \\ T_1^{(2)} \\ T_2^{(2)} \\ \vdots \\ T_n^{(2)} \end{bmatrix} - 2 : \begin{bmatrix} T_1^{(1)} & T_2^{(1)} & \cdots & T_n^{(1)} \\ T_1^{(2)} & T_2^{(2)} & \cdots & T_n^{(2)} \end{bmatrix}$$

where $n$ is the number of cells in the chosen direction as illustrated in Fig. 3. The optimization algorithm is implemented as series of MATLAB scripts calling QW-3D and QW-BHM when necessary.

The developed computational tools consist therefore of two pieces of software. The first one is dedicated to comprehensive coupled EM-T FDTD analysis of MW heating process occurring with varying applicator’s operating functions and resulting in some spatial distribution of temperature.
From the results of the analysis, it becomes evident that certain operating functions could be involved in an automated procedure looking for their best combination guaranteeing the uniformity of MW heating in the shortest time. The synthesis software is built as an optimization procedure determining the set of functions providing the best development at each heating step. A corresponding temperature field is taken for the computation at the next step. Once uniformity has been achieved, the code produces a full time-specific description of the optimal MW heating process. Both computational tools are conveniently controlled through the special graphical user interfaces.

CONCLUSIONS

In this paper, we have presented the algorithms and corresponding computer implementations which are used in the new approach to minimizing time-to-uniformity in MW heating systems [13]. Incorporation of all operating functions in our analysis and synthesis computational tools is enabled through appropriate post-processing implemented in the related MATLAB codes. Computational experiments showing a substantial (up to orders of magnitude) reduction in time-to-uniformity [13] have exemplified by series of 3D temperature fields illustrating processes of forming more and more even temperature patterns.

REFERENCES