

## Modeling-Based Synthesis of a Microwave Heating Process Producing Homogeneous Temperature Field

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**Abstract:** A fundamental problem of microwave thermal processing is the intrinsic non-uniformity of internal heating of a dielectric sample. This paper outlines an efficient technique for solving this problem with the use of numerical modeling and subsequent synthesis of the optimal process guaranteeing uniformity. The model relies on an iterative 3D FDTD solution of the coupled (electro-magnetic and thermal) boundary value problem. The algorithm is implemented as a collection of MATLAB scripts producing a description of the optimal process along with the final 3D temperature field. The functionality of the proposed optimization is illustrated by a computational experiment.

**Keywords:** coupled problem, FDTD analysis, microwave heating, temperature field, time-to-uniformity.

### Summary

Despite recent advances, the microwave (MW) power industry still suffers from the fundamental problem of intrinsic non-uniformity of the resulting internal heating pattern. We present here a general technique for solving this challenge. The approach is based on (a) an FDTD solution of a two-way coupled electromagnetic-thermal problem with temperature-dependent material parameters, (b) an effective technique for measuring the uniformity of the temperature field, and (c) our substantiated position that heat diffusion serves as the vital mechanism in achieving uniformity of heating.

The problem is formulated mathematically as finding the MW heating process which minimizes the time required to raise the minimum temperature of the load,  $T_m$ , to a prescribed goal temperature,  $T_{MIN}$ , provided that the maximum temperature,  $T_M$ , remains below a preset threshold temperature,  $T_{MAX}$ . Characteristics of the MW system, which, when altered, dramatically affect the resulting temperature pattern, are identified through the process of FDTD modeling and are chosen as the *operating functions* (or *design variables*) for the optimization. A pulsing regime (in which periods of thermal relaxation are allowed between periods of MW heating) is always included in the optimization algorithm to let heat diffusion reach the *cold spots* that cannot be targeted by MW heating given the specific set of design variables.

The optimization algorithm proceeds by choosing the combination of operating functions which creates the most uniform temperature field after each successive heating step. Temperature uniformity is measured then as the average temperature deviation corresponding to all neighboring pairs of FDTD cells representing the load. The optimization procedure produces a description of the optimal MW heating process with the resulting uniform temperature field.

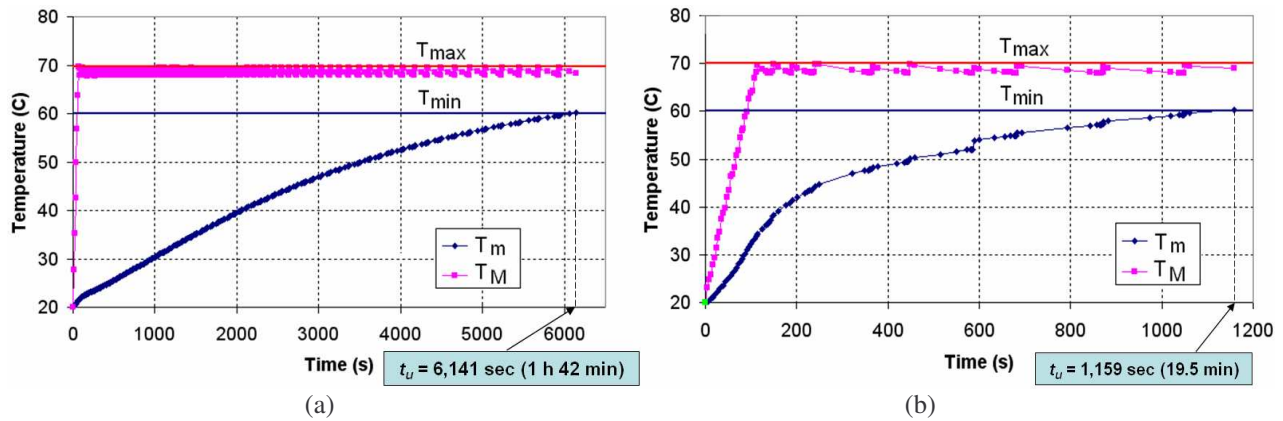


Fig. 1. Characteristic of heating processes using a pulsing regime (a) and using the optimization technique (b)

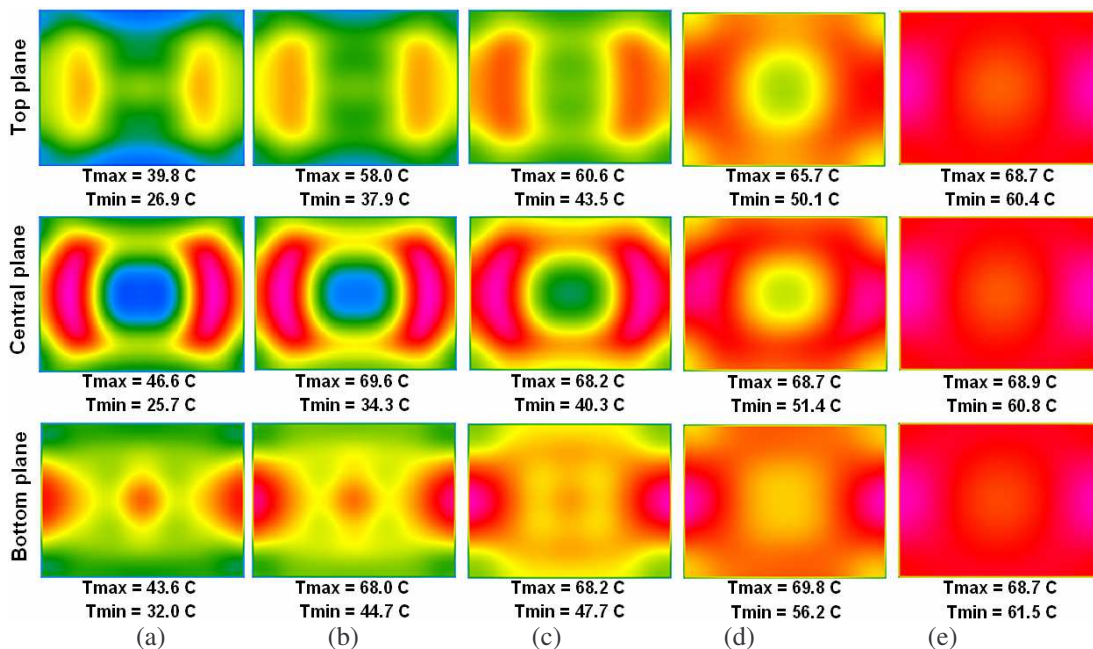


Fig. 2. Optimal heating process: intermediate and resulting temperature patterns in specific horizontal planes of the load after 56 s (a), 114 s (b), 177 s (c), 448 s (d) and  $t_u = 1,159$  s (e).

The developed computational tools are separated into two pieces of software. The first is dedicated to the two-way coupled electromagnetic-thermal FDTD analysis of MW heating which considers varying the applicator's *operating functions*. The software is given a series of commands which emulate the experimental process; the list of implemented commands includes the level of input power, the type of an exciting mode, position of the load, involvement of conventional heating, etc. The second piece of software acts as an optimization routine which determines the combination of these operating functions that provide the best development of the temperature field after each heating step. Both computational tools are developed using *MATLAB*. The solution of the electromagnetic part of the problem is achieved with the use of the 3D conformal FDTD simulator *QuickWave-3D* v. 6.5 [1]; corresponding temperature fields are computed with the use of *QW-BHM* [1].

The functionality of the proposed technique is illustrated here by a computational experiment which considers a single-feed rectangular cavity ( $248 \times 124 \times 180$  mm) operating at 915 MHz. It contains a

processed rectangular sample ( $85 \times 76 \times 25$  mm) imitating raw beef with dielectric constant  $\epsilon' = 55.3 \div 46.2$  and loss factor  $\epsilon'' = 22.2 \div 36.8$  varying in the  $20 \div 130^\circ\text{C}$  temperature range. The optimization process was performed using 4 s heating time-steps, in which MW power is turned off when  $T_M$  reaches  $T_{\text{MAX}} = 70^\circ\text{C}$ , and resumes when  $T_M$  has relaxed below  $68^\circ\text{C}$ . Using 1 kW of MW power, uniformity is reached in 20 minutes which results in a 5.3 times reduction in time-to-uniformity compared to the pulsing regime alone, as illustrated by the time characteristics in Fig. 1. The temperature field in the top, central, and bottom horizontal planes of the sample are displayed at various times in Fig. 2. These pictures illustrate how uniformity is reached during the simulation.

Practical CAD of a MW system providing uniform heating is thus reduced to the determination of suitable design variables for each particular scenario and their incorporation into the optimization process. The computational experiments show that our technique is capable of reducing the time-to-uniformity by as much as an order of magnitude (in comparison with a routine pulsing regime).

### Reference

- [1] *QuickWave-3D*<sup>TM</sup>, *QW-BHM*<sup>TM</sup>. QWED Sp. z o. o., ul. Nowowiejska 28 lok. 32 02-010 Warsaw, Poland, <http://www.qwed.com.pl/>.