Examination of Contemporary Electromagnetic Software Capable of Modeling Problems of Microwave Heating

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Introduction

Despite all the progress in numerical mathematics and computational technologies, computer simulation of processes and systems of microwave power engineering remains a new and unexplored arena for most practitioners. Engineers dealing with microwave non-communication applications currently seem to lack not specific technical data but general information on modern computational opportunities.

At the same time, a number of modeling tools do allow one to get valuable data about the characteristics of the considered system prior to constructing a physical prototype. The goal of the present paper is to update the database of the modern electromagnetic (EM) software suitable for the modeling of microwave heating and outline a few conceptual and practical issues associated with the efficient use of these simulators.

Software Database

The database of the EM software available in the market and applicable to the majority of problems of microwave (MW) heating has been recently introduced in [5]. The selection criteria for this database were set up to identify high frequency (HF) 3D simulators able (as a minimum) to determine return losses and compute the power dissipated in the processed material.

From Fall 2000, when [5] was sent to press, to the time of writing the present paper (July 2001), the contents of the database have noticeably changed. The market for the modern EM modeling software is very dynamic due to strong competition among the vendors. Since all the solvers were originally developed for the communication and high-speed electronics, these rapidly growing sectors are permanently demanding more adequate and sophisticated computations.

Many features of these newly developed tools can be of help for the practice of MW power engineering. Nowadays, the list of pieces of software suitable for this field includes 17 names of full-wave 3D EM simulators. These commercially available codes are produced by 16 vendors from 7 countries in Europe, North America, and Japan.

Table 1 contains the references to the solvers, which, to our mind, deserve the intent look of the engineers designing the microwave heating systems. Other codes from this database not shown in this table may currently be not as suitable as these ones: some of them run only under UNIX operating system (*EMFlex* by Weidingler Associates, Inc.), others are present only on the regional markets (like the Japanese codes *MAGNA/ TDM* and *JMAG-Works*). The term "actual use" means that the code has been used at least once in some R&D or industrial microwave heating projects; "potential use" indicates that the solver has passed the selection criteria, but the examples of its application in modeling of MW thermal processing are unknown.

Among the kernel computational methods, Finite Element Method (FEM) and Finite Difference Time Domain (FDTD) dominate; Transmission Line Method, usually considered quite similar to FDTD, is also available. FEM algorithms have been limited to the problems that are electrically not large because of the necessity to use too much memory. Nevertheless, because of their ability to accurately approximate complex structures with curved boundaries, two or three years ago the simulators based on the FEM could still be found more attractive.

However, today the time domain algorithms associated with the techniques for overcoming the difficulty conforming to curved surfaces (the FIT with the Perfect Boundary Approximation suggested by CST for *Microwave Studio* (*MWS*) and the conformal FDTD developed by QWED and implemented in *QuickWave-3D* (*QW3D*)) may appear preferable for many classes of problems in MW heating typically involving objects with complicated boundaries. These algorithms are able to handle larger problems, need less memory, are generally quicker than FEM algorithms, and are capable of naturally animating the field and power propagation in the structures. User-friendly intuitive graphical interface can be named among other advantages of *MWS*. *QW3D* has been recently supplemented by a number of options specifically appropriate for modeling of microwave heating [1]. Examples of successful uses of this software in modeling of systems of MW power engineering have been reported in [3, 4].

One particular option is noteworthy. Some EM codes from the database could be joined with the programs solving a thermal problem in the framework of a common computational process in which the results of the EM computations are used as input data for solving the heat conduction equation. For instance, *MAFIA* and *Multiphysics* can be easily connected with the corresponding thermal simulators available from the same vendors. The two solvers run subsequently and are governed by the user through the common interface. Possibility of coupling

Table 1. Modern Modeling Software Applicable to Simulation of the Test Problems (As of September 2001)

Vendor and Code	License & Maintenance	Kernel Method; Operating System
Ansoft Corp. www.ansoft.com *HFSS 8.0*	$42,000 12%	Finite Element Method; UNIX, Windows 95/98/2000/NT4
ANSYS, Inc. www.ansys.com *Multiphysics 6.0*	$40-45,000 call vendor	Finite Element Method; UNIX, Windows 95/98/2000/NT4
CST, GmbH www.cst.de *MAFIA 4.1*, *Microwave Studio 3.2*	$30-50,000 14%	Finite Integration Technique; UNIX, Windows 95/98/2000/NT4 Windows 95/98/2000/NT4
Faustus Scientific Corporation www.faustus.ca *MEFiSTo-3D Pro 2*	$10-20,000 20%	Transmission Line Method; Windows 95/98/2000/NT4
Flomerics Electromagnetics Division www.micro-stripes.com *Micro-Stripes 5.6*	$49,500 12%	Transmission Line Method; Windows 95/98/2000/NT4
IMST, GmbH www.imst.de *EMPIRE 2.2*	$12-20,000 from $1.5K	Finite Difference Time Domain Method; UNIX, Linux, Windows 95/ 98/2000/NT4
Matra Systèmes & Information www.emc2000.org *EMC2000-VF*	$30-35,000 (with interface) 15%	Time Domain Finite Volume Method; Windows 95/98/2000/NT4
Remcom, Inc. www.remcom.com *XFDTD 5.1*	$15,000 $3K	Finite Difference Time Domain Method; UNIX, Windows 95/98/2000/ NT4
QWED www.qwed.com.pl *QuickWave-3D*[a] *2.1*	from $15,000 15%	Conformal Finite Difference Time Domain Method; Windows 95/98/ 2000/NT4
Zeland Software, Inc. www.zeland.com *FIDELITY 3.0*	$20,000 15%	Finite Difference Time Domain Method; Windows 95/98/2000/NT4

[a] Also distributed by Vector Fields, Inc. under the name *Concerto*

[b] Optimization Systems Associates, Inc. (1983-1997)

[c] By Altair Engineering, Inc., www.altair.com

[d] Engineous Software, www.engineous.com

[e] Basic Heating Module

Table 1. (Continued)

Status in Microwave Power Engineering	Features of Performance, System Requirements, etc.
Actual use.	SAR (for plane wave). OSA[b] optimization. PC-to-UNIX simulations. Eigenmode solver for anisotropic materials.
Actual use.	Compatibility with other ANSYS products. Coupled HF/thermal solution, import of major CAD models, advanced animation.
Actual use.	SAR. *MAFIA*: up to 20 mil. cells. Optional temperature analysis. *Microwave Studio*: PBA, non-uniform meshing, AutoCAD and ACIS export/import, CAD design, optimizer, multithread solver.
Actual use.	SAR. 20 MB free hard-drive space from minimum installation. Multithread solver.
Potential use.	SAR. ACIS-based interface. Non-uniform meshing. Parallel solver functionality. Thin films. Minimum 400 MHz processor and 1000MB free disk space.
Actual use.	SAR. Auto CAD import (limited to 3D boxes). 300 MB hard-disk space.
Potential use.	SAR. 4 GB hard-disk space. *HyperMesh*[c] interface.
Actual use.	SAR. iSIGHT optimization[d]. Multiprocessor for FDTD
Actual use.	SAR. 45 MB hard-drive space for typical installation. Non-uniform conformal meshing, ACIS export/import, AutoCAD import, optimization. Optional multithread solver & BHM[e].
Potential use.	SAR. Non-uniform meshing, 1 GB hard-disk space.

exists also in *MWS*: its state-of-the-art VBA interface is open to quick user-specified modifications and connections with other computational tools. However, except for one project with *MAFIA* successfully conducted by Battelle several years ago (a microwave oven for drying of piles of wet books), no other attempts to couple the EM codes with the compatible thermal simulators are known.

Currently, the licenses cost from 10 to 50 thousand USD (with the average 31 thousand), and the maintenance varies from zero (for 2 years) to 7 thousand (with the average 3.9 thousand) per year. The present study was not supposed to bring justifications of the costs of the licenses; the financial information is given here just for preliminary orientation. However, the general trend appears to be as follows: the price tends to be higher when the work on the software took more resources and was based on a larger investment into the development of the user interface. The latter, for example, makes *MWS* interface more convenient and easier to learn and use than the *QW3D*'s one. At the same time, it has to be mentioned that appealing automated functions cannot guarantee adequacy and accuracy of modeling and have to be under permanent control of the user from which sufficiently high qualification in electromagnetics and numerical mathematics is certainly expected.

To complete the brief review of the database, it is important to emphasize that nowadays developments in HF EM computational technologies are very fast, so some data presented here, particularly related to extensions and supplementary functions, could become antiquated even before this paper is printed. For the updated data, the interested readers should contact the software vendors.

Test Problems

To estimate the efficiency and check out the computational characteristics of the software in the database, a few test problems resembling typical constructions for microwave thermal processing have been formulated to be modeled by those simulators. For example, there were:

(1) a 2.45 GHz 1 kW non-standard microwave oven [4] with a uniform spherical potato centered on a circular shelf of a finite thickness (Fig. 1, a);

(2) a 915 GHz industrial oven excited by two rectangular waveguides, featuring the bottom formed by two inclined planes, and containing a conveyor belt with the set of hamburgers.

It was supposed that the examined codes would be checked as to how they got the patterns of the electric field and the dissipated power and how they computed matching, coupling and some other parameters. While problem (2) turned out to be complicated enough for collecting more or less "uniform" results suitable for comparison, the computational data obtained for problem (1) allow us to reveal some conceptual issues in the modern comprehensive modeling of systems of microwave heating.

Results

Preprocessing

All the programs in Table 1 have capabilities to generate a concise 3D view of the scenario. Particularly convenient and flexibile graphical functions are available in the ACIS-based interfaces and the commercial post-processor *HyperMesh* (Fig.1, b). An alternative concept resides in providing parametarized libraries of typical elements and scenarios. This seems to be the approach taken by QWED.

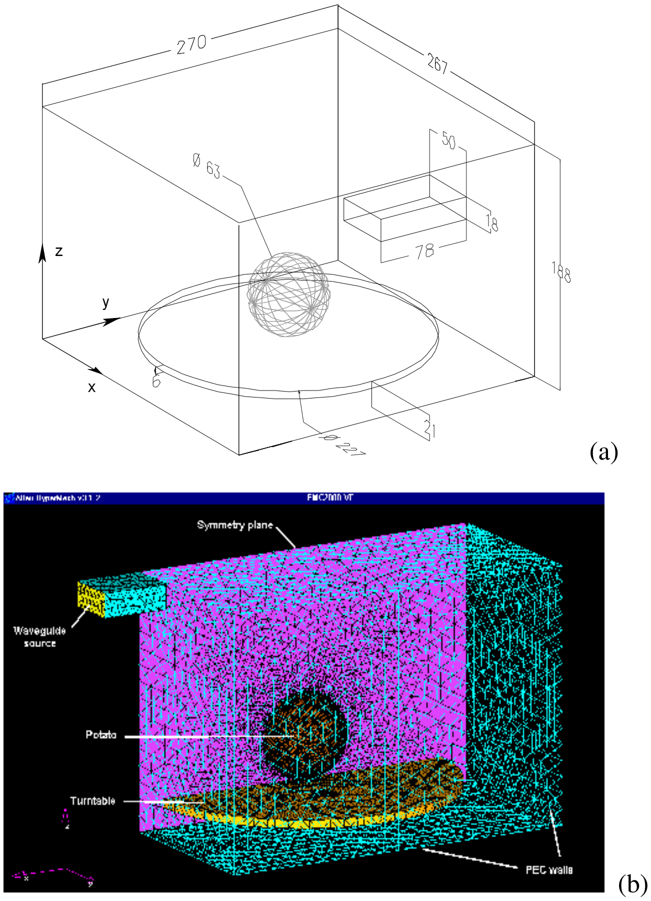
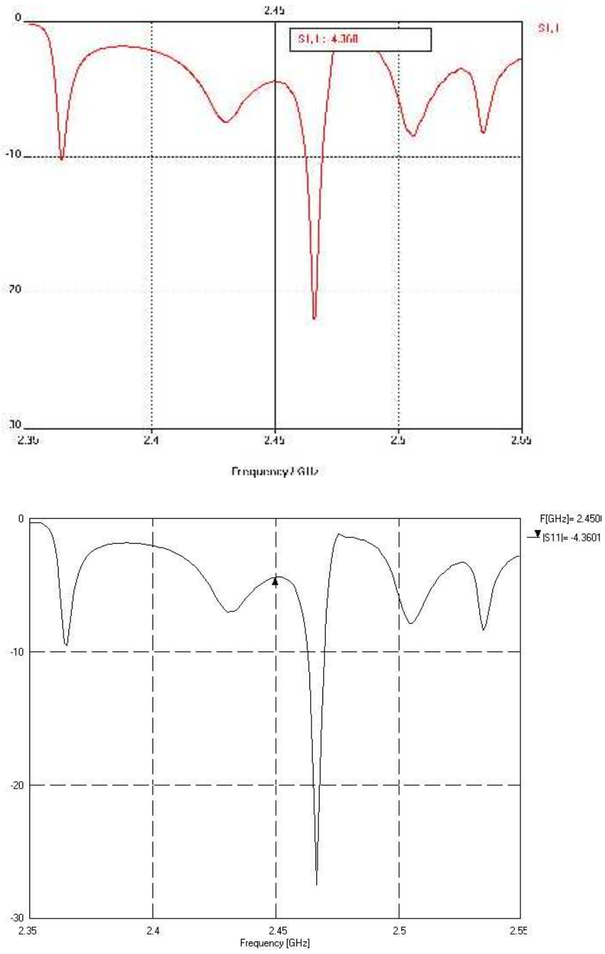


Fig. 1. Microwave oven with a spherical potato (permittivity ε = 65 – *i*20) on a microwave-transparent shelf (ε = 2.55 – *i*0) (a) and its reproduction by *EMC2000-VF /HyperMesh* (courtesy of Aerospatiale Matra, 2000) (b).

Reflections

When considering potential benefits from computer modeling, microwave heating engineers typically wonder how a particular simulator could help improve heating uniformity, but do not always appreciate the possibility to calculate the reflections both from the entire construction and its certain elements. The system is usually considered well-designed and properly operated if less than 10% of the energy supposed to be delivered to the cavity is lost due to all kinds of reflections [2]; in other words, the level of a return loss less than -10 dB is supposed to be small enough. Taking control over this characteristic is fairly important: the



(a)

(b)

Fig. 2. Return loss in the oven in problem (1) computed by *Microwave Studio* (courtesy of CST of America, 2001) (a) and *QuickWave-3D* (courtesy of QWED, 2001) (b).

reflections could be very high for some particular configurations of the cavity and parameters of the load; in addition, the cavities used for MW thermal processing are usually characterized by resonances. These factors may remarkably decrease the efficiency of the whole system.

All the codes in Table 1 (except *EMC2000-VF*) are capable of computing *S*-parameters of an analysed structure and thus determining S_{11} (the reflection coefficient) in the frequency range adjacent to the operating frequency and by this to clarify the important property of the cavity and its feed(s).

The return loss in the oven (1) have been simulated by *MWS* and *QW3D*. In the simulations performed on regular PCs, the first program used about 1.085 million cubic cells, while the second used approximately 1.002 million. In both cases, the applied mesh was non-uniform with smaller cell size within the potato (1.0 mm in *MWS*, 1.2 mm in *QW3D*) and larger in air (5 mm both in *MWS* and *QW3D*).
The two curves are shown in Fig. 2. The divergence in the value of S_{11} at 2.45 GHz is less than 0.2%. The graphs are very similar, so we can be confident that they both describe the reflections in the system quite adequately. The tiny differences in the curve shape can be attributed to the minor distinctions in meshing and in the number of time iterations in the course of simulations.

At 2.45 GHz, the system is characterized by the large return loss (about -4.4 dB, that means about 37% of energy is lost) whereas there is a strong resonance in the immediate neighborhood: in the range with a width of 4 MHz, S_{11} is less than -15 dB, which means that the energy loss at these frequencies is fairly low (not more than 3%). The peak, however, is too narrow, so this could bring no particular profit, but rather cause instability in the operation of the system: the range of the magnetron frequency deviation is typically about 50 MHz, and the width of the magnetron output spectrum may be up to 100 MHz.

Upon getting a characteristic of S_{11} like the one shown in Fig. 2 one may conclude (even prior to simulation of the dissipated power) that it would be unfeasible to build a prototype with the considered configuration because of its possible low efficiency. Since the position and the form of the resonance is primarily governed by the cavity dimensions, further computations (particularly with the use of optimisation options) could help find the dimensions of a system with reasonably low reflections (say, $|S_{11}| < -10$ dB) in a wider frequency range (about 50-100 MHz) around 2.45 GHz.

Electric Field

While for computation of *S*-parameters a circuit should be considered as excited by a pulse of frequency spectrum, simulation of the fields requires the sinusoidal excitation at a particular frequency. Although the structure of the electric field does not explain how the energy is released in the load, knowledge of the field pattern is essential for understanding of processes in microwave heating systems. The time-domain algorithms implemented in the simulators in Table 1 deal with direct

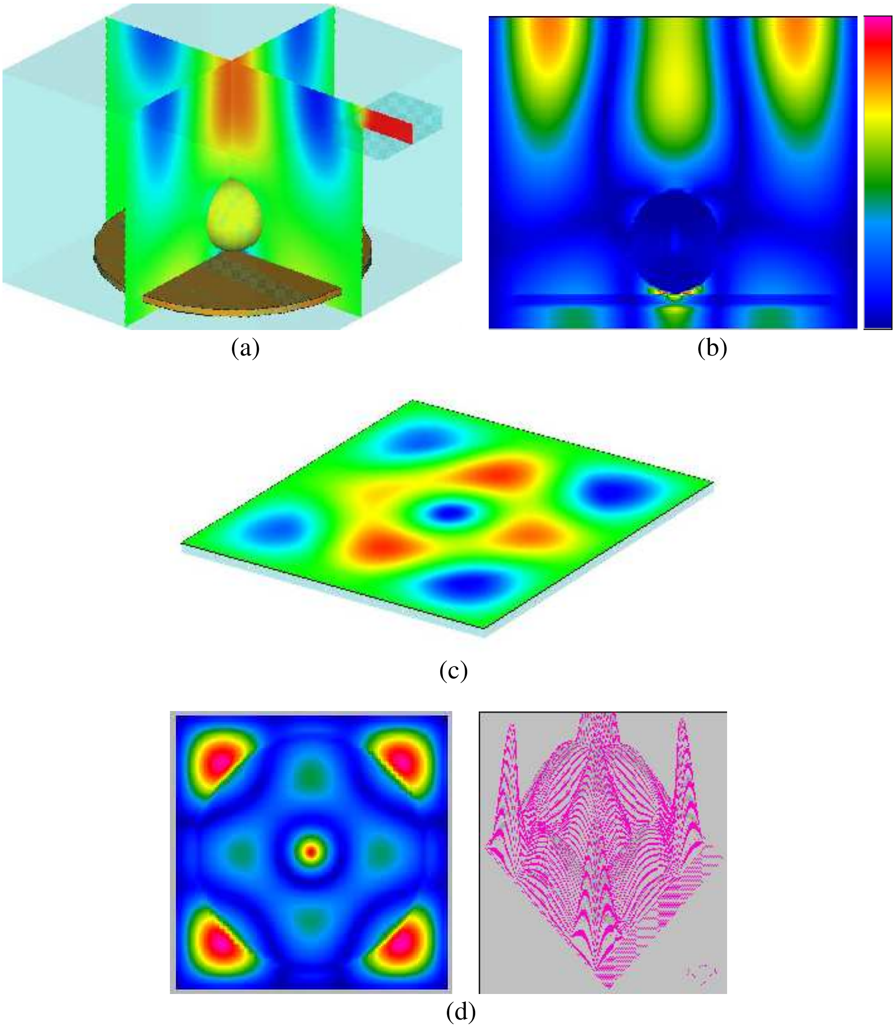
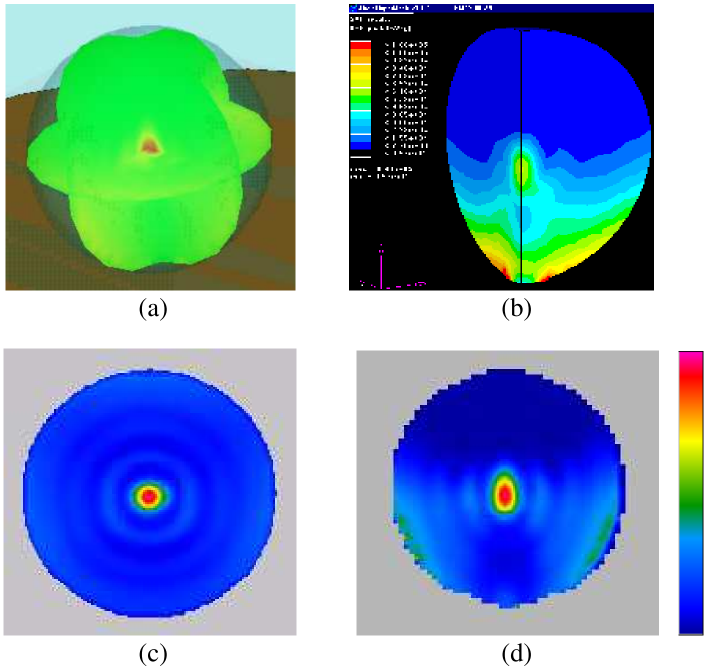


Fig. 3. The vertical component of the electric field in the vertical cuts through the center of the potato (a, b) and in the horizontal cut (10 mm above the oven's bottom) (c, d): instantaneous fields by *Microwave Studio* (courtesy of CST of America, 2001) (a, c) and field envelopes by *QuickWave-3D* (courtesy of QWED, 2001) (b, d).

numerical solutions of Maxwell's equations and thus handle the fields varying in time. The fields therefore can be naturally animated and visualized for different phases.

The patterns of the electric field at 2.45 GHz obtained by *MWS* and *QW3D* (using the meshes described in the previous section) and presented in Fig. 3 look quite similar and allow one to identify the mode as quasi-TE_{331}. Due to the high



(a) (b)

(c) (d)

Fig. 4. SAR patterns in the mutually perpendicular cuts through the center of the potato: *Microwave Studio* (courtesy of CST of America, 2001) (a), *EMC2000-VF/HyperMesh* (courtesy of Aerospatiale Matra, 2000) (b), *QuickWave-3D* (courtesy of QWED, 2001) (horizontal, (c); vertical, (d)).

dielectric constant of the potato, the field is much stronger in air which confirms the point that characteristics of the oven in problem (1) depend on the cavity dimensions rather than on the material properties.

Dissipated Power, SAR, Energy Coupling

To show how microwave energy associated with the determined field is released in the potato, simulation of the dissipated power or SAR is required. Fig. 4 presents the SAR patterns within the product computed by *MWS*, *QW3D*, and *EMC2000-VF*. (Since the potato is uniform, the patterns of the dissipated power look similar, differing only in scale.) It is seen that there is a strong "hot spot" in the center of the potato; in accordance with the *QW3D* simulation, the magnitude's max/min ratio in the vertical pattern (Fig. 4, c) is about 120.

The result appears to be consistent with the focusing effect in spherical objects well described in literature for the plane wave. *MWS* and *QW3D* generate practically identical patterns whereas *EMC2000-VF* suggests higher level of the dissipated power on the bottom surface of the sphere. This discrepancy can be attributed to the fact that the latter code does not simulate the modal excitation of the cavity (the dominant TE_{10} mode of the waveguide feed), which in fact takes place, but approximates it by the plane wave whereas *MWS* and *QW3D* reproduce the waveguide modal excitation scrupulously.

As seen from Figs. 3, 4, post-processor functions of *MWS* and *EMC2000-VF/Hypermesh* allow the user to get convenient quasi-3D views showing patterns in the mutually perpendicular coordinate planes. Conformal FDTD computation performed by *QW3D* receives conformal visualization only in the horizontal plane (Fig. 4, b) whereas the display in the vertical plane is simplified and does not show the actual shape.

The percentage of the power absorbed by the processed material with respect to the power generated by the magnetron (coupling) was rigorously calculated by *QW3D* through an average power dissipated in a sinusoidally excited system. In oven (1), it was found to be equal to 67.8% of the power delivered to the cavity. The coupling C can also be approximated after the first run of the simulator with the pulse excitation from the formula

$$C \cong (1 - \left|\overline{S}_{11}\right|^2)100\% ,$$

where $|\overline{S}_{11}|$ is the module of the reflection coefficient at 2.45 GHz, without the need of analysing a sinusoidally excited system. From *QW3D*'s computation of reflection, C appears to be 63.4%, i.e., the divergence with the rigorous computation is about 9%. The possibility of estimation of coupling brings another argument in favor of computation of reflection preceding the runs for the field and SAR patterns.

Temperature Patterns

In the beginning of 2001, the version of *QW3D* designed specifically for microwave power engineering was released. It includes the so-called Basic Heating Module (BHM), which allows the user to compute and visualize the temperature patterns in the processed material taking into account the fact that its material properties (complex permittivity, density ρ, and specific heat capacity c) are changed as functions of dissipated power. BHM does not deal with the heat conduction problem, but computes temperature T at the moment m+1 in accordance with the formula:

$$\begin{aligned} T^{m+1}(x,y,z) &= T^{m}(x,y,z) + \frac{P(x,y,z)\Delta t}{\rho^{m}(x,y,z)c^{m}(x,y,z)} \\ &= T^{m}(x,y,z) + \frac{H^{m+1}(x,y,z) - H^{m}(x,y,z)}{\rho^{m}(x,y,z)c^{m}(x,y,z)}, \end{aligned}$$

where H is the enthalpy density, and Δt is the assumed user-specified time of heating at a particular steady-state with constant average power P. However, the adequacy of this approach appears to be reasonable for many applications, so the presence of such an extension in the EM solver obviously provides more opportunities for detailed and advanced modeling of processes of microwave heating. Yet, the functions offered by this module surpass the options that the present study suggests as sufficient for the valuable analysis of the formulated test problems; these functions are therefore not considered here.

Conclusion

This paper has presented the updated database of the modern EM simulators suitable for modeling of problems of microwave power engineering. The collected results have shown the advanced capabilities of the time domain solvers (*Microwave Studio* and *QuickWave-3D*) and emphasized their practical usefulness in modeling reflections, the electric field, dissipated power, and energy coupling. Both simulators perform very well in the basic EM simulation. Currently, *QuickWave-3D* appears to be particularly useful for designers of applied and industrial systems of microwave heating due to a number of implemented specific extensions and functions beneficial for the field (such as field envelopes, energy coupling, BHM, and others). Strong dedication of the vendor to the field is also noteworthy.

The study did not have the aim of comparison of the kernel computational methods implemented in the simulators, but it rather focused on their current technical adjustments to the needs of the field of microwave power engineering. With the wider participation of other software in solutions of the suggested test problems, more specific information about particular features of the solvers could be revealed. Evaluation of the EM modeling tools is going to be continued in the framework of comprehensive benchmarking, which means solving a typical and meaningful microwave heating problem by the different simulators with the subsequent experimental validation.

The way the simulators were used for the analysis of problem (1) can be beneficial for other systems of microwave power engineering. It appears to be feasible to start computer analysis with the pulse excitation and getting reflections in the frequency range adjacent to the operating frequency. This should give a general understanding of the EM processes in the system and perhaps suggest certain changes in the initial design – for instance, if return loss in the adjacent frequency range is characterized by strong resonance(s). Then the excitation has to be switched to the sinusoidal one so that the field and the dissipated power could be computed and visualized. A convolution technique implemented in *Microwave Studio* allows one to extract the sinusoidal fields at the several frequencies from the broadband calculation, so just one simulation is necessary to obtain both the behaviour of *S*-parameters in the frequency range and the harmonic field at a user defined operating frequency.

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