	height/[mm]	diameter/[mm]	contact angle	p_K/[N/m^2]
0.1 kV	1.49	4.05	70.14	59.04
10.4 kV	1.11	4.41	60.50	92.74

It is conspicuous, that the difference $p_K(10.4\text{ kV}) - p_K(0\text{ kV})$ in the pressure of curvature is nearly the same as the force density $\vec{f}(10.4\text{kV})$.

5 Conclusion and Outlook

The simulation of the behavior of water droplets on polymeric surfaces under the influence of an applied high–voltage field is a demanding task. The first step, the numerical calculation of electric field strength and force density, is presented here. The result of the droplet measurements is our assumption, that the difference $p_K(\text{x kV}) - p_K(0\text{ kV})$ of pressure of curvature approximates well the force density during increasing voltage. We will validate this hypothesis by more measurements and simulations.

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Commercial EM Codes Suitable for Modeling of Microwave Heating - a Comparative Review

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Abstract Electromagnetic modeling software available in the market is studied in accordance with specific criteria to compose contemporary database of codes applicable to designing industrial systems of microwave thermal processing. Operating systems, kernel computational methods, interfaces, optimization options, possibilities of solution of associated thermal problem and financial information are among the basic characteristics addressed. It is shown that sixteen selected codes are very differently adjusted to practical needs of the field. Vendors are rated with respect to their dedication to the microwave power engineering. Issues related to further evaluation of the codes (solution of benchmark problems) are discussed.

1 Introduction

The recent remarkable increase in the quality of modeling and the certain decrease in the costs of software and hardware have caused a substantial growth of the use of advanced computer simulations in designing wireless telecommunication equipment, computer systems, networking and other products.

Although engineers dealing with microwave non-communication applications have also become more interested in modeling, for most, this arena remains new and unexplored. The review of commercial EM codes [1] written for users in the telecommunications field does not include any indication as to what extent these codes are convenient for modeling of microwave heating. The only paper [2] outlining the concepts of numerical methods suitable for microwave thermal processing was published 10 years ago. Many cases of successful modeling in R&D projects have been reported, however, they have not specified the use of simulations in design of industrial systems. The microwave power community currently seems to be lacking not just specific technical data, but very general information on modern computational opportunities [3].

The present paper looks at the software market and considers the capabilities of particular codes with respect to the needs of microwave power engineering. The results are represented in the form of a software database with discussion of the issues associated with the further analysis of the codes.

2 Rationales

Despite all the progress in numerical mathematics and computational technologies, microwave thermal processing still cannot be modeled in its entirety. No modeling packages can provide complete information about processes, which necessarily involve thermal conduction. Neither can one take into account such phenomena as water transport, evaporation, mass transfer or chemical transformations and reactions. Corresponding research does exist, but there is no computer code implementing numerical solutions of all these problems at once.

Today, valuable results can be obtained from simulation of electromagnetic and thermal processes. All applicable software can be divided into two groups in accordance with this feature. Another classification identifies academic and commercial codes. Judging the latter appears to be difficult: published information is far from complete. The academic codes can be often working tools in the hands of no one but the authors. It would be perhaps unrealistic to suppose that much university software can be used in industry.

As for codes for analysis of thermal processes, they might be useful in practical situations. However, in the present review, we assume that the electromagnetic phenomenon plays the primary role in efficient microwave heating and is essentially responsible for the entire process.

Therefore, we focus here on EM commercial codes. Initial purpose was to discover what software available in the market can be efficiently used to help analyze and design systems of microwave processing. The subsequent objective is to study the most promising codes and work out certain generalizations and recommendations to the microwave power community.

3 Selection Criteria

All codes can be divided into two groups as implementing algorithms for low frequency and high frequency (HF) electromagnetics. Since at HF mathematics is more complicated, the number of packages applicable to this field is smaller (some 30%). Among codes in this smaller group, there are packages dealing with 2D approaches and oriented on planar structures, as well as codes addressing open problems and beneficial for electromagnetic compatibility, antennas, etc. We ignore these tools as irrelevant to the present study and reduce the size of the market to a very limited number of codes.

The remaining packages were exposed to the criteria on the software capabilities. The characteristics determined by numerical methods can be listed in order of increasing complexity. The part of the list relevant to problems of microwave heating may be presented as follows:

- Eigenfields in presence of lossy materials; power of the eigenmodes;
- Fields excited by the given source;
- Dissipated power of the excited fields;
- Specific absorption ratio (SAR) patterns;
- Level of coupling.

It seems for practitioners in the microwave power industry it would be feasible to have software with the capability of calculating the dissipated power of the excited fields *as a minimum.* Finding eigenfields may not be enough for

the purposes of industrial design: these data require certain interpretation; it might make sense in R&D projects though. So only codes able to determine at least patterns of dissipated power are analyzed below.

Commercial Electromagnetic Software of Actual/Potential Use in Microwave Power Engineering (August 2000)

Vendor	Code	Operating System & License/Maintenance per year	Status, Major Technique, Performances, Requirements, etc.
Agilent Eesof EDA[1] www.tm.agilent.com/tmo/hpeesof	*Agilent HFSS Designer 5.5*	UNIX, Windows 95/NT4 *call vendor*	Actual use. FEM.DP.OSA[2] optimization, PC-to-UNIX simulations
Ansoft, Corp. www.ansoft.com	*Ansoff HFSS 7.0*	UNIX, Windows 95/98/NT4 $42K/12%	Actual use. FEM. DP, SAR (for plane wave). Eigenmode solver for anisotropic materials.
ANSYS, Inc.	*ANSYS/ EMAG*	UNIX,Windows 95/98/NT4 $25-30K/ *call vendor*	Actual use. FEM. DP. Compatibility with ANSYS CAD codews, advanced animation.
CRC Research Institute, Inc. www.crc.co.jp	*MAGNA/ TDM*	UNIX, Windows NT4 *call vendor*	Potential use. FDTD.DP. 2 years on Japanese market; no English manual
CST GmbH www.cst.de	*MAFIA 4*	UNIX, Windows 95/98/NT4 $9-50K/10%	Actual use. FIM.DP,SAR. PBA: up to 20 mil.cells. Optional temperature analysis
	Microwave Studio 2	Windows 95/98/ NT4 $10-50K/10%	Actual use. FIM. DP, SAR PBA, AutoCAD export/import Full CAD design
ElectroMagnetic Applications, Inc. www.csn.net/~emaden	*EMA3D 3.0*	UNIX, Windows NT4 $14-27K/ $2.5-4K	Potential use. FDFD & FDTD. EMA-FAM[3] interface
IMST GmbH www.imst.de	*EMPIRE 2.2*	Linux, UNIX, Windows 95/98/ NT4 $12-20K/ from $1.5K	Actual use. FDTD. DP, SAR. Auto CAD import (limited to 3D boxes.) 300MB hard-disk space
Infolytica, Corp. www.infolytica.com	*FullWave*	Windows 95/98/ NT4 *call vendor*	Potential use. FEM. DP. Advanced interface
The Japan Research Institute	*JMAG-*	UNIX,Windows NT4	Potential use. FEM & FDTD.

Commercial Electromagnetic Software of Actual/Potential Use in Microwave Power Engineering (August 2000)

www.jri.co.jp	*Works*	$35K/*call vendor*	DP. Thermal solver; 2GB hard-drive.
Matra Systems & Information emc2000. matrasi-tls.fr	*EMC2000-VF*	Windows 95/98/ NT4 $15-20K (w/interface $30-35K)/15%	Potential use. TDFV.DP,SAR. 4GB hard-disk space. *HyperMesh*[4] interface
Remcom, Inc. www.remcom.com	*XFDTD 5.1*	UNIX, Windows 95/98/NT4 $15K/$3K	Actual use. FDTD. DP, SAR. iSIGHT optimization[5]. Multiprocessor for FDTD.
QWED www.qwed.com.pl	*QuickWave 1.9*	Windows 95/98/ NT4 $15K/15%	Actual use. Conformal FDTD, DP, SAR. 15MB hard-disk space ACIS export/import, AutoCAD import, optimization.
Tech Univ. of Hamburg-Harburg www.tu-harburg.de/~tebr	*CONCEPT II 8.0*	Linux, UNIX $26K/ 2 years free	Potential use. MoM. DP, SAR. 100MB hard-drive space
Weidingler Assoc., Inc. www.wai.com	*EMFlex*	UNIX $40K/ *call vendor*	Potential use. FETD. DP. Optional thermal solver
Zeland Software, Inc. www.zeland.com	*FIDELITY 2.0*	Windows 95/98/ NT4 $20K/ *call vendor*	Potential use. FDTA. DP, SAR. 1GB hard-dsk space

NOTE: DP = Dissipated Power. SAR = Specific Absorption Ratio. FEM = Finite Element Method. FETD = FE in Time Domain. FDFD, FDTD = Finite-Difference in Frequency Domain and Time Domain. MoM = Method of Moments. FIM = Finite Integration Method. TLM = Transmission Line Method. TDFV = Time Domain Finite Volume. PBA = Perfect Boundary Approximation.

[1]Formerly Hewlett Packard Eesof. [2]Optimization Systems Associates, Inc.; purchased by Hewlett Packard in 1997. [3]FEGs, Ltd., www.fegs.co.uk. [4]Altair Engineering, Inc., www.altair.com. [5]Engineous Software, www.engineous.com.

4 Analysis

Table 1 includes the names and main characteristics of the 16 full-wave 3D codes, which fulfill the selection criteria. Each code exists in either one, or several versions for various operating systems. Today, 14 out of 16 packages work under Windows NT. A few years ago, UNIX associated with workstations or supercomputers was the only option for efficient EM codes. Now this big disadvantage for the industry is over.

The software status in the microwave power engineering is specified by two terms. "Actual" means that it has been used at least once in some R&D or industrial project whereas "Potential" indicates that all capabilities outlined above are available. Currently, the Actual/Potential ratio is equal to 8/8.

Among the kernel computational methods, FEM and FDTD prevail, but the method traditionally considered less powerful and flexible (Method of Moments) is also available. Dissipated power and SAR are identified as the key parameters, which can be calculated and visualized. SAR is not now an option in all codes; however, vendors say that since calculating one on the basis of the other is simple, this would be added if any customers request it.

The interfaces appear to be very different. Agilent and Ansoft have developed for their own advanced interfaces. *Microwave Studio, Empire,* and *QuickWave-3D* offer advanced functions for export/import data to work with some CAD software. *EMC2000-VF* merely works with another piece of commercial software, *HyperMesh*, serving as an interface.

Another important feature is an optimization option. It is present in *Agilent HFSS 7.0*, *Ansoft HFSS 5.5*, *QuickWave-3D 1.9*, and *XFDTD 5.1*. The option implements a certain procedure of computer optimization, i.e., a subsequent solution for various scenarios with the choice of parameters supposed to be the best in accordance with some specified criteria. Running this option may take much time, but it might be useful.

Two vendors have implemented practical solutions of how to overcome the major disadvantage of the classical FDTD: the stair-like approximation of the mesh cells. The incorporation of the so-called Perfect Boundary Approximation in *Microwave Studio* and the Conformal FDTD in *QuickWave-3D* allows an accurate modeling of curvilinear regions.

Interested users can work now with at least 3 vendors exploring an opportunity of solving the EM problems in association with the thermal ones. CST and Weidingler Associates promote thermal packages completely compatible with their *MAFIA, Microwave Studio* and *EMFlex*. *JMAG Works* exists as the set of compatible modules including the thermal code.

The interactive profile of this study has allowed us to determine the vendors' rating regarding their dedication to the MW heating applications (Table 2). The companies in the first column exhibit very little interest in the area. The 2-star vendors are aware of microwave heating applications and admit that they may have certain involvement in corresponding technical support and further development of their products. QWED heads the list,

Table2. Rating of Vendors' Dedication to MW Heating Applications

*	**	* * *
Agilent, CRC RI, EMA, IMST, Infolytica, JRI, Remcom, TU H-H, WAI, Zeland	Ansoft, ANSYS, CST, Matra S&I	QWED

demonstrating a real desire to work for the field. Some features specifically appropriate for the microwave heating (specified modal excitation, field envelope, etc.) are already available in their code. Also, the company has recently announced implementation of special regimes for running *QuickWave-3D* in applications with thermal changes of media parameters.

Each code has a variety of options and configurations, and the license costs depend dramatically on that; the average is $26,500. The average cost of the maintenance (technical support and upgrade) is $3,000.

5 Examples: Benchmark Problems

To make specific evaluation of the selected codes in the context of particular needs of the microwave power engineering and determine recommendations, further study of the database is needed. It is supposed that solutions of a series of benchmark problems (BMPs) should give data for comparison of the efficiency of the codes and their computational characteristics. The problems have to be associated with typical systems of the field a possibility of independent (e.g., experimental) verification of the results.

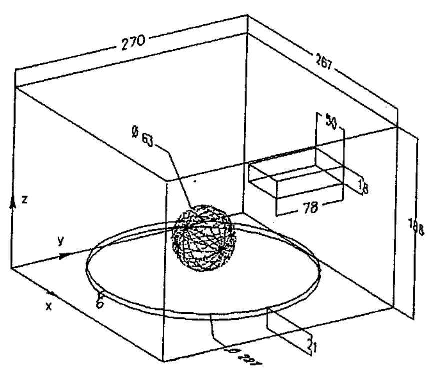

Figure1. The configuration of the BMP models with the potato.

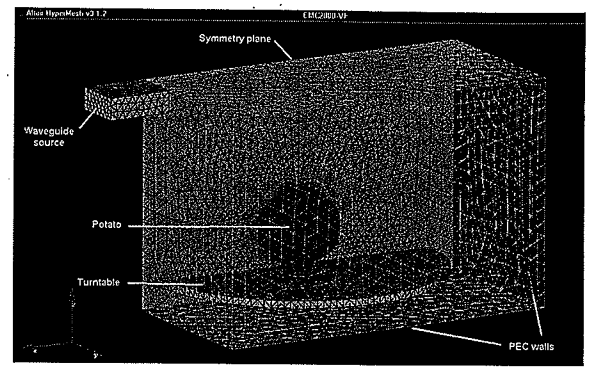

Figure2. Interface image of the BMP (a) created by *EMC2000-VF/HyperMesh*. *Courtesy of EADS - Matra Systemes & Information, www.emc2000.org, 2000.*

The structure chosen for the first BMP is based on the microwave oven designed by Per Risman [4]. The cavity is excited by one magnetron (frequency 2.45 GHz, average power 1 kW) through a waveguide feeder; the walls are of perfect electric conductivity. The problem deals with two different processed materials: (a) uniform potato centered on the shelf; (b) two-layered pizza centered on a microwave-transparent platform located on the shelf. The sketch of the oven is shown in Fig. 1.

The potato and pizza are approximated by spherical and cylindrical two-layer models respectively. The potato is supposed to be uniform and characterized by relative permittivity $\epsilon = 65 - i20$ and density $\rho = 1.0\ g/cm^3$. In the pizza, the lower compact layer is of $\epsilon = 6 - i3$ and $\rho = 0.25 g/cm^3$; the upper soft layer possesses $\epsilon = 45 - i20$ and $\rho = 1.1 g/cm^3$.

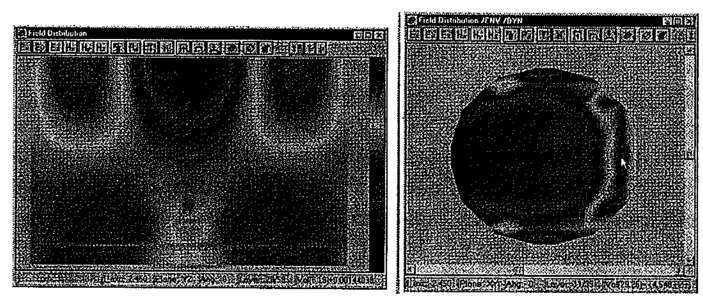

Figure3. Examples of *QuickWave-3D* simulation: the electric field (E_z) in the vertical cut (yz-plane)(left) and the SAR in the horizontal cut (right); the central planes of the potato. *Courtesy of QWED, www.qwed.com.pl, 2000.*

The expected output includes: (a) patterns of the electric field, dissipated power and SAR in the vertical and horizontal cuts; (b) coupling, i.e., the reflection factor for the frequency range and specifically at the operating frequency and percentage of the magnetron power dissipated in the materials.

The full-scale solutions of the BMPs by all 16 codes is probably unfeasible. The luck of the some vendors' interest in the microwave heating applications may mean that at the present time their products could not really provide comparable/competitive data. Initial results are currently available from the two- and three-star vendors. Fig. 2 reproduces the model of the BMP (a) as it is shown in the *EMC2000-VF's* interface. The patterns of the electric field and SAR calculated by *QuickWave-3D* are shown in Fig. 3. These examples do not pretend to be either genuine benchmarking results, or meaningful simulation data; they are rather simple illustrations of what commercial codes can provide for the microwave power industry.

6 Conclusion

All 16 full-wave 3D EM commercial codes applicable to microwave heating modeling were originally developed for communication applications, so they adapt to MW heating problems quite differently and thus should be carefully considered in association with the current application. Expenses associated with the software should be analyzed in the context of possibility to reduce the traditional expensive and inefficient cut-and-try phase in industrial design of the systems.

This review has suggested software database for non-communication microwave engineering. Presently, with the set of general characteristics and features, the paper might be *food for thought* for engineers and practitioners. Anticipated results of benchmarking should shed light on efficiency of the codes and show to what extent some of them could be convenient in the use in practical industrial projects.

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