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Parallel Worlds of Microwave Modeling & Industry: A Time to Cross?

Complete Uncut Version

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Despite the permanent progress in the microwave heating technologies, the conventional impossibility of generating a desired (uniform) heat release within the product remains the key problem for practical applications. It is becoming evident that taking advantage of the computational efficiency of modern computers and software in order to simulate systems and processes is one of the most radical ways of improvement of performance of microwave heating. In the past, the phenomenon appeared to be too complicated to be modeled adequately. Recently, however, some very advanced approaches have been developed and much progress has been made towards more realistic and beneficial modeling.

On the other hand, while efficient mathematical techniques find certain applications in today's R&D efforts, they remain far from real use in food processing and other industrial applications. Companies manufacturing equipment for microwave heating either do not know about the existence of computer models and software, which could remarkably assist them with solutions of their technological problems, or do know but, for various reasons, do not use them. Users of the equipment usually do not think of this at all; their attempts to fit a system to some

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process are purely experimental. The present paper outlines circumstances that causes such separated positions of industry and modeling, and speculates about the evident necessity of the use of appropriate models and software for efficient design, manufacturing and application of microwave heating systems.

It would probably be no exaggeration to point out that so far the vast majority of applied work in the area of microwave energy has been done on the basis of advanced intuitive perceptions and engineering expertise. The entire industrial sector has been developing for all this time without full-scale modeling of the produced equipment, but it seems that the field has been able to progress nevertheless.

However, in the years to come, *can it continue to progress as well as it is anticipated, if it continues using the same intuitive methods? Will the traditional experimentation design allow the industry to pursue any real challenges in the new millennium?* The suspicion that the answers to these questions may be negative has been one of the key factors that initiated the appearance of this paper.

Recent History

A remarkable growth of publications addressing issues in the mathematical modeling of microwave power systems has been observed since the end of the 1980s. Coming mainly from universities and small research teams and illustrating results of R&D studies, these papers have provided the community with better understanding of features of microwave thermal processing. Though obtained under a number of serious idealizations and simplifications, the electromagnetic fields and energy deposition have been computed for a variety of applicators and in processed materials of various configurations and electrophysical properties. A few publications have even addressed a coupled electromagnetic and heat conduction problem. The status of math modeling in pre- 1990 and 1995 R&D studies was evaluated in [1] and [2] respectively.

Two more obscure major projects carried out in the end of 1980s and beginning of 1990s are worth mentioning. A consortium of corporate sponsors supported a 3-year research project at SIK, Göteborg, Sweden, towards the development of advanced computational techniques for modeling of systems of microwave oven heating of foods [3]. At about the same time, Alcan

International, LTD, Kingston, Ontario, internally funded a program for a similar purpose [1]. Compared to the original ambitious goals, the results of these projects were moderate, at best. It was revealed that the simulation, which would be desirable for designers of microwave equipment and ovens, could not be reached at that time on the basis of available algorithms and hardware.

Nowadays, computer technology is progressing incredibly quickly, and the flood of the studies using numerical methods and computations in connection with processes and problems of microwave power engineering is becoming more and more enormous. This may be illustrated by a simple quantitative characteristic: the number of such papers published in 1996-1999 only in major periodicals and conference proceedings[1] approaches 80. The finite difference time domain (FDTD) technique and finite element method (FEM) considerably dominate in this period (see Fig.1).

While the majority of the work has been done on the basis of original algorithms and software developed by their authors, there is also evidence that some researchers have been using commercial modeling packages to simulate their systems (some relevant details are considered below). However, there are just a few examples of that. Much better known to specialists in communication applications, these packages possess a lot of options making them, in fact, *universal* and applicable to numerous problems of related to microwave technology in general. The use of commercial software non-adapted to the specific features of microwave power engineering is, however, far from obvious, so the authors who have succeeded in such computations justly consider their work to be a meaningful achievement.

Absence of Good Software – Matter of Fact or Annoying Delusion?

When asked about mathematical and computer modeling with respect to their work, companies dealing with microwave thermal processing display a well-defined yet paradoxical opinion.

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[1] 14 issues of *Journal of Microwave Power & Electromagnetic Energy* (N 1 1996 – N 2 1999), four volumes of Proceedings of the *IMPI Microwave Power Symposia* (1996-1999), the Proceedings of the *MRS Microwave Processing of Materials V Symposium* (April 1996), the Proceedings of *the 6th AMPERE Conference on Microwave and HF Heating* (September 1997), and the Book of Abstracts of the *1st World Congress on Microwave Processing* (January 1997) have been checked.

Today's position of an ordinary engineer in industry appears to involve a whimsical mixture of skepticism and interest. First of all, there is a belief that nothing that would be both easily handled and useful really exists – and is not horrendously expensive. There are no modeling utilities, they say, that do not have to be very heavily adapted in order to be used with the types of problems on which they are working. Since the models that exist have been made for applications such as communications, radiolocation and accelerators, they may have limited use, if any, in their practical needs. The commercially available software is very difficult to learn; the academic packages are not configured to be used by anyone other than their authors. Both of them are believed not to be easy enough to use, not having a convenient dialog interface, and unwieldy when considered for a diverse set of modeling problems.

Industrialists also question adequacy of what available math models and software can do and what the design and construction of industrial equipment require. There is an assurance that all that the computations can deal with are overly idealized or simplified models whereas real materials and processes are much more complicated (non-uniform, non-isotropic, with non-smooth boundaries, temperature-dependant, etc.).

At the same time, the evidence of successful research simulation of some systems and processes may not stimulate any sort of neglecting of this field. It seems that the entire microwave power community is being embedded into an *atmosphere* of general friendliness and respect regarding mathematical modeling and computations. Representatives of industry demonstrate certain curiosity and interest as well, apparently hoping that something appropriate will emerge somewhere around; the signs of their serious thinking about *computation preceding the experimentation* are obvious.

Thus, on the one hand, there are a lot of results of R&D modeling, but on the other hand, there is practically no use of modeling in industry. Are all these studies of such low value that nothing produce any impact on real industrial practice? Alternatively, is the industry so backward and/or indifferent to the advanced computational technologies?

Neither this, nor that. Many publications implement really sophisticated techniques of numerical analysis and suggest ideas for effective technological solutions and improvement of characteristics. Commercial packages extensively progress and offer today some unprecedented computational opportunities. However, the viewpoint of the industry doesn't result from insufficient awareness or ignorance. It has grown on a real specific experience. Microwave power industry is known as a highly competitive sector, so those who work there permanently look for various prospective applications and efficient technologies. Being IMPI members, key personnel of the industrial companies have access to all relevant publications and always attend major events in microwave power communities, such as the Annual IMPI Symposia and the Biennial AMPERE Conferences. They even may possess some information from microwave communication community. Thus, virtually all notable achievements that involve relevant modeling and computations are typically known to industrial people. But practically in all cases they could not determine if any of the results/techniques/software would directly apply to any of the prevalent problems that they encounter. In other words, *so far they have not been convinced of their practical usefulness*.

How could this happen that the situation is still so inconsistent?

Miscommunication in the Age of Communications

It appears that one of the main reasons for this inconsistency is the lack of appropriate communications between modeling and industrial fields. Or, speaking openly, *there are no proper communications at all*. Each party lives its own life and does just what it has to do. Engineers dedicated to design and production of microwave ovens and industrial power equipment try various crafty adjusting devices to improve heating performance. They vary the position and number of energy inputs, invent mechanical means to mix up the energy contribution from different electromagnetic modes, check shielding and packaging of various fashions, etc. Everything is done on the basis of engineering intuition and experience, and sooner or later it helps, and after extensive captivating experimentation, the system operates somehow, though the details of *why* and *what* was useful remain unclear. Then the installation is shipped to a customer, and the design of a new unit for the next client starts in the same manner.

As for analysts and modelers involved in academic R&D, they realize well how mathematically fascinating and complicated the modeling of microwave heating is, and are happy to find themselves surrounded by a thousand and one relevant things to do. Wandering in the jungle of theoretical aspects of modern numerical techniques, fighting against matrices of sizes too huge to fit computer resources, pursuing efficiency of computation and adequacy of visualization – these and many other challenges require deep penetration into the maze of computational math and familiarity with today's computer technologies. Sooner or later, concluding these laborious studies, an algorithm is created, a program is composed, and computations are performed. Usually, modelers work in a team with technicians, so the results are validated on an experimental set up. Then the output of the project is described on paper and/or presented in conference. But the interest of the authors in this work is typically diminished afterwards in favor of the next project.

Hence, there are two groups of narrowly specialized experts working in the areas of their expertise. They exist practically independently. Important events may happen in one community without any involvement of another. A big company may join in a new work having no opinion of a modeling expert about its features. An academic team uses any opportunity to start a R&D project no matter how industry assesses its potential for future application. The parties feel that they are supposed to be in certain interaction, but they are too busy with their own work.

Moreover, each side has a fairly vague notion about the more or less subtle issues in the activities of another. Engineers suspect that modeling efforts in academia are generally not too adequate to the industrial requirements and do not go beyond playing with symbolic/scientific meanings and abstract numbers that certainly may make sense, but not for them. In their turn, modelers grow wise with experience in computations of microwave heating systems and suggest that current industrial production is inefficient, or even primitive, because various opportunities of potential efficiency revealed in their mathematical and computational studies are not taken into account.

These opinions are unlikely to be completely adequate, but quite logical. Too little effort yet has been made to work out common positions and mutual acquaintance. Industrialists do not address modelers with questions on how to calculate *this* or *that*; they are fairly confident in their own empirical approaches. Modelers in academia like to bring people in and solve problems for them, but without actually bringing the software into the field. This way, some of them even produce an impression that they don't care about their reputation in the industry's eyes.

Here is a story. A software is presented by the leader of a university team known due to its many ambitious presentations and publications in modeling of microwave power systems. It is described as an advanced modern tool ready for the direct use in simulation of practical industrial situations. The team's leader proclaims the necessity of amending the relationship between academia and industry and announces that for this reason they offer the software to interested companies *for free*. A leading engineer affiliated with a major manufacturer of microwave industrial equipment, having an interest in the efficient modeling of his equipment and attracted by this opportunity, expresses the desire to test the software and asks the professor to send it to him. Shipping and handling is enthusiastically promised... but not done. The second and third requests are forwarded, and each time, after proper apologies, sending is promised again. Nevertheless, the package is never sent. Most likely, the professor has just been very busy, and the software is not a myth and in fact is as good as described. But no surprise that since this story happened the industrial manufacturer has become more restrained in contacts with modeling people from academia and more skeptical regarding the possibilities of advanced computations in his business in general.

Two Other Groups

The preceding subdivision of people whose work is relevant to the subject of this paper into the groups of university modelers and industrial engineers is, however, incomplete. At least two other groups can be identified. First, there are *consumers* in different application areas. They do not produce, but use microwave systems for their particular processes. Companies having access to ovens/equipment for microwave processing of some *specific* products frequently try to apply them to heat other materials including those whose composition and properties are unknown; many examples of unsuccessful projects of this sort have been reported.

In contrast with the equipment designers who may regret that (for some reason) there is no possibility for them to try computer simulation/design in order to enhance characteristics of their producing systems, the vast majority of these people is absolutely unaware of this option. Result: the funding allocated for their projects is spent in vain, and the companies become disappointed in microwave technology in general. It seems that no meaningful initiative regarding computer simulations of their processes has ever been generated by the consumers.

Companies designing and developing commercial modeling software represent another group. Nowadays, these computational tools include complete RF and microwave electromagnetic, circuit, and system simulators integrated in a graphical environment. So far, their software has market in the communications businesses, thus the packages have been oriented on such areas as design of antennae, feeds, microwave and RF circuits, etc. Everything is done to help communication design engineers achieve results faster and with higher than ever accuracy – from design concept to production.

Being universal, these packages are *potentially* applicable to microwave ovens and other heating equipment; however, no special tools, regimes, interfaces, or other options are available. The designers of commercial software are, of course, aware of the microwave processing applications, and this area is interesting for them since it requires advanced numerical mathematics and computer technologies to be involved. However, they do not have any demand, or notable feedback from the microwave power engineering, and, in the absence of promising market, the packages are not properly adapted. In order to use them for simulation of ovens or other equipment one has to possess a certain level of knowledge in numerical techniques, electromagnetic field theory and computer technologies even in order to appropriately *prepare input data* and *interpret results of computations*. As a matter of fact, the possibility of existence of experts of this level among consumers of microwave heating equipment is nonsense, and it may be exotic even in the companies manufacturing this equipment.

Secrets and Bucks

The impact of the following two issues is also noteworthy.

Companies in the microwave power industry vary in size and capital turnover, but perhaps all of them belong to the so-called small business. Purchasing a commercial package and dedicating the time to their learning, hiring programmer(s) and/or modeling specialist(s), developing company's own comprehensive software, and other similar things, – all this requires remarkable financial resources; for some businesses, that can be one of the company's largest expenditures. Indeed, the qualification of a specialist who could be responsible for this type of work in an industrial company is estimated as an MS (at least) or Ph.D. in an appropriate field and with relevant working experience. Several years ago, the costs of commercial software were up to 50 K. Thus, in most cases, software-assisted modeling activity required monetary latitude that the companies merely could not afford.

Another point is technological security. Strong competition in the field and the fight for orders enforces companies to hide almost everything. Issues even remotely related to technological solutions are never revealed, even to non-specialists. In the context of our topic, this means that a company would prefer to struggle against its technological problems on its own, rather than to ask help from modeling experts. The latter might know simple solutions suggested by their computational experience. But since such a contact would mean a transfer of information outside the company, such an alternative often does not exist – even when the cost of the service would be very reasonable. The decision not to share information with anyone is actually a reflex. No analysis of economical benefits of such collaboration is undertaken. Confidentiality is first and foremost.

It appears, therefore, that financial limitations and issues of technological secrecy are additional factors making the relationship between modeling and industry very difficult. Their combination with other indications considered above creates a very complicated and depressing situation, and it is fairly unclear how to approach its resolution.

However, there are signs of hope. The increase of industry's interest in modeling is a sort of *sufficient condition*, and it is undoubtedly taking place. And it is possible to consider the most recent progress in numerical techniques and computational tools to be the *necessary condition*.

What's Available?

This progress has, first of all, resulted in a number of advanced commercial software available by the date and applicable to the problems of microwave power industry. The major packages are listed in Table 1.

Some of this software (such as ANSYS/Emag, EMFlex, FIDELITY) is only of potential application (at least, examples of their use in simulating microwave heating processes are not known to the authors), whereas other program have been successfully used and even have certain history of application in microwave power R&D projects. This can be said about a finite element package HFSS by Hewlett-Packard and Remcom's XFDTD, which implements a finite-difference time-domain technique.

The functional capabilities of these packages are not too different. In general, XFDTD can do 70-80% of what HFSS does, but, attractively enough, it is about 1/5 the cost of the HP package. At the same time, there is one feature of application of XFDTD to processes of microwave heating: making the scenarios proves difficult. Isolated facts of the simulation of microwave heating systems with the use of MAFIA and EMAS are also known.

In the past 3 or 4 years, there has been a significant increase in the pace of change in what is commercially available; the market has remarkably grown. New versions of HFSS, MAFIA and XFDTD have been announced, and new software (KCC Micro-Strips, FIDELITY) has been introduced. McNeal-Schwendler Corp., a creator of EMAS, reported on the change of its priorities and sold EMAS to Ansoft, Corp., one of the leading companies in the electromagnetic computer modeling.

In 1998, Hewlett-Packard Company announced that it had acquired Optimization Systems Associates, Inc. of Ontario, Canada, a company specializing in optimization technologies used with device-, circuit- and electromagnetic-simulation software. Integrating OSA's optimization capabilities into its 3D electromagnetic simulator, HFSS, HP expected a paradigm shift in how this tool moves from being analysis tool to design one.

However, in the same year, HP made a marketing decision *to terminate support of this package as a tool for microwave power engineering*. This does not mean that this package is technically inapplicable to the field's problems any longer. Rather, this is an indication that it is unlikely for a user to find in HFSS a lot of options that would be especially useful for computation of the most important parameters of their microwave systems. And another meaning: HP does not believe that it may have any reasonable selling in this field in the near future. This decision is an explicit illustration of how the lack of market demand controls the company's policy and puts it in an unfavorable pose with respect to the entire industrial sector.

About three years ago, Polish software, QW3D, has been introduced. The authors of this program have made a large amount of preliminary progress in development of both efficient numerical solutions of problems of applied electromagnetism and techniques of effective computer representation. The software based on these methods has been already recognized as the current state-of-the-art – many laboratories around the world use this software for the simulation and design of their components.

QW3D is a set of program products specialized in different classes of operations; at least two of them are required for full-scale computation of typical microwave heating systems. QW-Editor includes a graphical geometry editor, parametric object generator, input-output dialog, media libraries, and automatic mesh generator. QW-Simulator, in particular, consists of geometry compiler, 3D FDTD kernel, postprocessor, fast interactive display, module of exporting results and dumping fields. Among the innovative features of QW3D are: special tools for improved approximation and visualization of irregular geometries, distinguishing closely spaced modes and degenerating polarizations. The accuracy of computation remains high and stable even for scenarios with multicomponents, curved or sloping loads, thin wires, complicated susceptors, etc.

During the last year, the microwave power community had several opportunities to be introduced to this package and learn its technical features because Per Risman has plunged into extensive exploration and utilization of the software. He published results of the modeling of a microwave oven loaded by a pizza [5] and gave comprehensive presentations reviewing his experience in the software's applications to a variety of problems of microwave power engineering at two last the IMPI Symposia [6].

Risman refers to QW3D as an extremely powerful and versatile tool. Having an experience in working with other modeling software, he estimates its capabilities and productivity to be twice as much as the HFSS package. Regarding the interface, its convenience and flexibility is assessed as acceptable. But it is not like a CAD program; there is some difficulty. This software has many features that were previously unavailable in modeling program, so it is necessary to actually take a course before one begins to use the software and interface efficiently.

The results of a typical computation of a model described in [5] (an oven with a two-layered pizza on a susceptor of larger diameter) are presented in [7]. This model represents a pizza on a thin microwave-transparent platform elevated above the bottom surface of the oven. There is a lower soft layer and a top compact layer of different permittivities (6 - *i*3 and 45 - *i*20, respectively). The diameter and resistance of a susceptor under the pizza are also specified and taken into account. The spatial resolution in the pizza is 1.5 mm.

The QW-Editor image of this construction is shown in Fig. 2. This example of the QW3D's interface demonstrates sufficient specification of the system and convenience of its visual representation. In Fig. 3, the heating pattern in the susceptor is presented. It should be noted that modeling of such a thin and high-loss film is very difficult or even impossible with other modeling FDTD software, and FEM methods give in such a case a very poor resolution, at best.

Another example of microwave heating presented in [7] is about the electric field in the vertical plane in the cavity through the center of a spherical load lying on a non-rotating turntable and corresponding to a potato (permittivity 60 - *i*16). The field distribution is shown in Fig. 4. It is clearly seen that there is a resonant mode in the cavity, and its vertical index is 1. (Further analysis identifies it as the TM_{331} mode.)

Other software in Table 1 also may work well for the field and be especially efficient for some particular goals. Being the current owner and further developer of EMAS, Ansoft suggests a way of more advanced modeling of processes of microwave heating [8]. By coupling the electromagnetic analysis capabilities of EMAS with the thermal capabilities of MSC/NASTRAN[2], the power loss density and temperature variation within the product can be found without analyzing the full model twice.

Fig. 5 illustrates an example of such an approach. Using EMAS, electromagnetic analysis of a microwave oven containing a potato is performed. The power loss densities in the potato are calculated. Then, by incorporating the results of the EMAS analysis with an MSC/NASTRAN analysis, the temperature variation in the potato is determined. Heat transfer boundary elements are used to simulate the air flowing around the potato, without having to model the air, thus reducing the model size and computer time. However, such a model, involving *two* commercial packages of different specialization, is more expensive.

Last but not least, the costs of the software in Table 1 are very different. They depend on many factors, and primarily on terms of license agreement and configuration of the package. Today's average assessment is consistent with the values suggested by Risman a year ago [5]: good and useful software for a single user may cost from $10 to 15 K, and subsequent full-scale support and upgrade from $3 to 5 K per year.

So the current state of the market of the modeling software reveals that there are possibilities for advanced computer simulation and design of systems of microwave heating. It seems that this might be even *feasible* today. In the meantime, does the picture described above

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[2] McNeal-Schwendler's NASTRAN is a powerful finite element package providing, in particular, solutions for thermal analysis and optimization. The heat transfer capability of the package provides solutions to steady state and transient thermal analysis and design problems. This capability may also be used in combination with the MSC/NASTRAN structural analysis to perform thermal stress analysis [9]. Because of its original developer, EMAC is completely compatible with NASTRAN.

coincide with expectations of manufacturers and users? In other words, as far the computer modeling is concerned…

What Does Industry Want?

It appears that by the present time many engineers involved in design of microwave ovens and other heating equipment have already taken more or less insightful looks at the modeling opportunities and assessed them with respect to their practical needs. How do they describe software that would fulfill their expectations?

First of all, their major requirement is that a package has to be simple enough for an engineer to use it after a relatively short period of adjustment. It would be great to be able to set it down for a couple of months and pick it up again without having to relearn to use it.

Regarding the interface, the industrialists wish that both the input and the output be extensively visualized. A convenient way to provide input for a microwave device, they say, is to have a routine that could import a 3-dimensional object out of a CAD program into the modeling program. This object is to be coupled with material characteristics (in particular, the real and imaginary parts of permittivity), and this process has to provide an intuitive touch to the input portion of the graphical interface.

This idea comes from the fact that 3D "physical" computer tools are known to engineers as pretty powerful. One can create well-crafted 3D pictures with relatively inexpensive packages. So, having a mechanism to import these objects, it should be possible to get a "mechanical" description of a solid in space, set some microwaves loose on it, and look at what happens at a specific location in the substance.

The engineers would like to have software where they could plug in the boundary conditions of the physical systems that they are building and, basing the calculations on these boundary conditions and the physical geometry of the various dielectric structures and absorbing/conducting structures inside the system, have the software tell them what the field profiles and heat release would be.

Industrialists are aware that commercial EM software containing features like these has been available for a while. The point is: most of them also contain *various extras that raise the price of the product*. If it was possible to have packages of *reduced configuration*, i.e., consisting of primarily those options that are required for the needs of microwave power engineering, that would be a strong precondition for their distribution in the field.

Designers and manufacturers emphasize the necessity for modeling software to be able to run on PCs under Windows (either 95/98, or NT). The UNIX operating system supporting multiple user workstations and supercomputers and preferable for complicated computations has virtually no use in this industrial sector.

And, at last, people in industry have yet to see the software in operation. In order to become convinced that the product is exactly what will make them happy, they need to gain an experience in getting really useful and helpful computational results with its assistance.

The review of the available software leads to the conclusion that some of these requirements could be satisfied right away. Practically all of them are available on Windows 95/98, so present day desktop computers appear to be good enough to run them. HFSS, QW3D and other packages offer their own extensive libraries of geometric objects, and software designers currently work towards making images from popular CAD packages compatible with their products. Other requirement, such as configuring/reducing the packages in accordance with the field's needs may become a reality if corresponding market emerges in the field. However, the simple wish to have simple tools seems to be unrealistic.

Although the new situation on the software market makes microwave modeling possible and affordable, *it does not mean that the requirement of user's knowledge in microwave theory and engineering has been reduced*. Microwave thermal processing is a very complicated phenomenon, and tools for its comprehensive analysis unavoidably involve a lot of things, which should be controlled by an analyst. Hence if industrialists decide to model their systems themselves, they have to undertake an effort to learn a software and find out how it should be handled to bring maximal benefits to their projects.

R&D Itineraries in the New Context

The availability of the mentioned powerful commercial computational tools does not mean that everything is clear now with simulation of microwave heating systems. There is no reason to admit that researchers in academia have nothing to do now since their commercial competitors have already brought on the market everything that industry may wish to have. The entire situation is quite vague and intricate, and many conceptual issues still require clarification. At the present time, at least two of them are worth defining as the key R&D objectives.

Coupled Problems. The software gathered in Table 1 is purely electromagnetic[3] and able to handle Maxwell's equations under specific boundary conditions and compute the space distribution of electric and magnetic fields, power deposition, heating intensity, etc. So far, none of the commercial packages have been offering options for modeling of applied problems of microwave heating in their entirety, i.e., including characteristics of other distinctive physical phenomena. These packages cannot provide valuable information about microwave processes, which necessarily involve thermal conduction. Moreover, for processing of food products, for example, complete models should take into account not only heat transfer, but also water transport and, in some cases, mass transfer, evaporation, irradiation, and some chemical transformations. Thus what contemporary (EM) modeling actually addresses is just one element (though it is definitely a key element) in the multiplicity of physical phenomena forming the microwave heating – the electromagnetic aspect.

Beyond it, analysts have traditionally been focusing their attention on the major combination: the microwave modeling and thermal analysis. The *real* solving of the coupled problem of electromagnetism and heat conductivity means handling *simultaneously* Maxwell's equations and heat conduction equation. In other words, one has to deal with a system consisting of very different differential equations (PDEs of the 2nd order and ODE of the 1st order). In addition, their boundary conditions are very unlike.

Complete solving of the coupled boundary problem is a severe challenge; in fact, in the more or less general setting, the problem has not been rigorously solved yet. Application of numerical techniques is also extremely complicated and requires huge computer resources. So, usually, the coupled problem is analyzed on the basis of one crucial observation. Compared to the rate of change of high frequency electromagnetic fields, variation of the heat parameters is very slow (mathematically, less by several orders of magnitude), thus, within the period of variation of the electromagnetic field, the heat characteristics might be considered constant.

[3] There are also non-electromagnetic commercial packages (FIDAP by Fluid, Inc. and others) simulating heat transfer and applicable to processes of microwave heating. Examples of their successful use are also known (see, for example, [10]), but not considered in the present brief review.

Hence the electromagnetic field might be computer from Maxwell's equations and the electric field substituted into the heat conduction equation, and the latter can be solved independently.

This approximation simplifies the problem since it actually *separates* the electromagnetic and thermal analysis. It is supposed that this approach works well for processes of quite fast heating by microwaves and materials with low thermal conductivity. In the meantime, plenty of practical situations do not fall into this category. Whatever one does, however, for solving the coupled problem, dealing with it is a really time- and resource-consuming business.

Therefore, it would be reasonable to see a comparison of solutions to a practical problem obtained by microwave modeling *only* and by solving the electromagnetic equations *coupled* with the heat conduction equation. The purpose of this experiment would be to see how meaningful the power deposition (in one sense, the heat distribution at time zero) is in the final heat distribution of the product.

The question is*: how much would adding the coupling of the thermal equations improve modeling*? Having an answer to it, it would be possible to figure out for what processes solving the coupled problem is really required, and for which one the EM modeling solely works fine. For people in industry, the obtained cost to benefit ratio might be a highly valuable parameter.

What makes the present situation different is the fact that this study could be performed with (at least, partial) use of commercial software by those who earlier worked towards creating and developing their own algorithms and package. Continuing doing this now, when such advanced and affordable packages are available on the market, may make some specific sense for these people but unlikely for the industry. Rather, their experience in numerical methods and modeling of microwave heating systems could be an excellent precondition to success in these meaningful comparative studies.

Such work would be also extremely important to software designers since they could decide whether or not it is worthwhile to take this possibly most natural, but not necessarily the most sensible step in the development of modeling. That could be a way for constructive partnership of software vendors and academia.

In addition to heat conduction, mass transfer, water evaporation and transport, irradiation might be the dominant mechanisms for some practical processes of microwave thermal processing. So far, considering all these phenomena along with the EM problem are the open areas of research.

Optimization. Another major R&D objective is making the computer-oriented design and optimization of systems of microwave heating possible. Clearly enough, without these options the application of even highly sophisticated software brings only results of *analysis*. However, no suggestion is worked out towards improving the system or amending its performance. So, currently, the modeling can only be used as a (partial) replacement for the actual building and testing the microwave designs. If it could be used to optimize microwave heating, its market success would most likely increase.

The fact that the modeling implementing a pure analysis may not practically mean too much for designers and engineers was first discussed by Magnus Sundberg three years ago in [11]. Since the genuine goal of the engineer's work defined him as "*How should I design my oven/package/food so that the criterion is fulfilled?*" requires "*some kind of optimization*", he offered a simple but useful approach of this sort[4]. It actually means the need of computing parameters for a large number of applicator configurations, and searching for the best of them. For each case, a complete computational "cycle" should be performed, and then a computer has to process the results and choose the one in accordance with certain criteria.

But the most efficient modern numerical techniques (FDTD and FEM) need substantial time for computation of each scenario. So in 1996, in order to implement it practically, Sundberg suggested to use at this point the method of moments, neither so powerful, nor accurate, and applicable only to certain classes of systems, but requiring much less time. The approach was helpful in designing the tunnel oven [12].

A 1999's question deserving study: *can FDTD or FEM be fitted in an efficient optimization procedure now*? It looks like the answer is being actively searched for. At least two companies, QWED and Hewlett-Packard, pretend that their packages, QW3D and HFSS, based on finite-difference time-domain and finite element methods respectively, possess optimization options. QW3D uses the modified Powell method and offers a user-selected goal function. Techniques technologies developed by OSA and being implemented in HFSS optimizer require specifying design space and optimization goal. Vector Fields, Inc. and other vendors claim to have made efforts in this area as well.

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[4] It should be noted, however, that the term "synthesis" featured in the title of [10] was obviously chosen as an *emotional goal* rather than a rigorous mathematical term associated with the proposed approach.

All these techniques belong to the group of *computer optimization*. They incorporate the procedure of complete numerical solutions and in fact look for the extrema (minima/maxima) of multivariable functions. The capabilities of such approaches seem to be limited. They become available mainly due to the remarkably increased productivity of modern computers and thus need to rely on computational technologies. In the meantime, there is a *mathematical optimization* technique allowing one to avoid such a dependence. In contrast to the computer optimization, this approach does not include entire computational "cycles", but from the very beginning offers the optimality conditions that characterize the desired solution. Typically, a great amount of analytical work precedes the relevant computations. But this is a worthy effort since now it comes instead of so much of extensive calculations. The total number of examples handled through the analytical tools is, however, fairly low.

The Optimal Material Design is among those mathematical techniques that seem to be capable to put the heating intensity under direct control. In [13], the use of concept of OMD has been suggested to secure a desired distribution of heat release within processed material in waveguide systems. The use of this and similar approaches is, however, restricted to fully deterministic systems including materials with well-determined properties and shapes and applicators with finite number of participating modes. Also, so far, the OMD techniques have been developed only for control and optimization of 2D (traveling wave) system.

Therefore, at the present time, the link between computer simulation of systems of microwave heating and their optimization looks quite weak, and for this reason optimization appears to be a very important area of prospective studies. In fact, this subject even requires conceptual discussion since a lot of applied systems (such as multimode ovens with turntables) are non-deterministic *by definition*. When a process is completely unpredictable, what could one optimize?

Conclusive Remarks

Could the industrial and modeling businesses be brought together? It seems that in spite of all obvious misunderstandings and miscommunications in their relations today, there are enough preconditions for this.

The majority of industrialists believe that powerful, not very expensive modeling software with a convenient interface is not available, but, as it was shown above, that is not true. At the same time, there are certain trends that the industry starts to feel that its traditional intuitive methods of design and construction have already brought the field as far as possible and are going to be exhausted. In this situation, sincere attempts to figure out the real feasibility of the use of commercial software look like a naturally initiated search for challenges. And there are definitely worthy products to choose from.

Nowadays, vendors of the EM software suitable for modeling of microwave heating systems appear not to be too interested in this field because of one simple reason. They have a big and dynamic market for their products among communication businesses, and estimate the microwave power engineering as a low potential field. A growing demand from there would certainly change their orientation, and the packages could be adapted to the specific features of the heating systems to be modeled.

However, a few simple things could be recommended to the vendors right now. Making *shareware versions* of their products available and widely accessible to the potential clients in this field appears to be highly important. This would allow people in industry to satisfy their desire to try software in servicing their current projects. Analysts in academia could check if they find it reasonable to work with the package in the areas of their research and even work out recommendations regarding strategic and tactical principles of their use.

In the surroundings of lack of information regarding the computational opportunities, the available software, especially those packages robust enough for industry, must be made known to its audience. To achieve this goal, a possible strategy would be shrewd advertising. It would be useful if software designers warmed up their interest in the actual needs of microwave power industry and thought of certain simplification of their products for this area (particularly, of further improving interfaces).

In this ways, universities may become more active in establishing links with, and providing information for, the industrial sector. Also, academic research in the field would open the lines of communications for any new developments in both industry and academia. More close information exchange could supply universities with specified data on the typical problems and needs of the field. Eventually, there may appear a feedback in the form of results of R&D projects.

Now, if the fact that adequate software coupled with user-friendly interfaces, is available, is made known in industry and simulation proves to be more helpful than to just replace the actual building and testing of designs, then modeling software may indeed have more than a chance to be more widely used in the microwave power industry.

Acoustic *Cold & Hot Spots* Are Over. What About Microwaves?

Everyone who has ever attended a soccer or hokey game on an open/roofed stadium remembers how difficult it is sometimes to catch the name of the player who scored the goal. Any announcement made through the local audio speakers is hard to understand, whether you are inside a roaring crowd or stay aside during a quiet pause. In such a place, even music, should it occasionally play, often sounds like a messy rumble. But this looks natural. Acoustic conditions are highly inappropriate in these premises, so the audience is content with what it has – indeed, a stadium is not a concert hall; it was built with no care of sound.

Recently, however, the visitors of some sound-risky public spaces have surprisingly found themselves in amazingly enjoyable sonic environments. This happened after the audio systems were redesigned and rebuilt there by Bose Corporation.

This audio equipment manufacturer's innovative approach to designing audio systems possesses a number of advanced features, but there is a keystone. It uses special modeling to simulate the sound characteristics of an auditorium before placing speakers there. A computer is used to create a model of the planned facility, and virtually everything is taken into account – location and form of seats, slope of the floor, type of carpet (if any), etc. Such an approach allows Bose to provide the highest quality of sound for each particular premise[5]. The sound from the specially designed speakers is directed precisely into places where the public is, rather than all over the place, so one hears announcements clearly every time, enjoys the sound from every seat, and may even thrill from the vocal timbre and intonations of each audio presenter.

Acoustic environments of stadiums and arenas generating echoes and reverberations might be thought of as a good analogue to systems of microwave heating with their *hot and cold spots* within the processed materials. Not all hokey stadiums are equivalent sound-wise: some of

[5] In addition to sport arenas (for example, Madison Square Garden in New York City, Heysel Stadium in Brussels), Bose has re-equipped sound systems in General Motors Place in Vancouver, Sistine Cappella in Vatican, and in other places [14].

them are slightly better, others are slightly worse. Sound engineers checked various positions for the speakers, tried different brands, experimented with directed sound. The challenge has been, however, achieved only with the use of *detailed computer modeling* of each particular space.

The same thing happens here. Systems of microwave heating vary in internal constructions and size, in location of the input of energy, in processed materials, etc.; the problem of providing uniform heat distribution for microwaved substances actually remains unresolved. Is it not logical to think about the more advanced and detailed computer modeling?

Indeed, acoustic problems are much simpler to be mathematically solved, so, taking into account all technical preconditions, the full-scale simulation of sound environment looks not too complicated compared to the systems of microwave thermal processing. But the acoustic mess can be overcome now. What is next? How about the heat release in microwave systems? May the acoustic challenge serve as an example to follow?

Our analysis shows that by the present time, there are numerous premonitions pointing towards bringing the communities of modelers and manufacturers together. New computational technologies have appeared, and looking for challenges in their production, industrialists have begun to seriously consider their work in the context of computer simulations. More steps towards each other are needed.

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Post Scriptum: The Industrial Microwave Modeling Group. The observations outlined above suggest that so far the relationship between mathematicians and software developers on one hand, and microwave power engineering and relevant industrial sectors on the other, is under no coordination or control. It is, rather, in the state of disorder and mess. People from the two fields have trouble finding a common language. Many issues appearing to be relevant to both parties require analysis, clarification, and study.

In this situation, the foundation of an institution dedicated to the enhancement of the communications between the parties seemed to be necessary, and the corresponding step has been taken by the Department of Mathematical Sciences at WPI. The Department's Center of Industrial Mathematics and Statistics (CIMS), working as a mathematical resource to industry, has established the **Industrial Microwave Modeling Group (IMMG)**. In general terms, the major objective of the new institution is to enhance the technological competitiveness of its industrial partners and thus enrich the experience of the faculty and the value of the student's education. More specifically, the Group serves as a special intermediary between manufacturers and users of microwave equipment and ovens and the software designers in order to:

(i) extend the use of modeling in industry (and ultimately reduce the cost of manufacturing of equipment, ovens, and materials/food, and improve their characteristics), and

(ii) provide relevant feedback regarding the upgrading of modeling software to make it consistent with the actual industrial needs.

The IMMG is active in various forms. It possesses efficient modeling software (from both academia and commercial designers, including listed in Table 1) and makes them available for demonstration to potential industrial users. Trial computations can also be done. Information support is available for microwave industry regarding contemporary computational opportunities and for software designers regarding the requirements of the industrial sector. Research activity is mainly focused on the techniques of control and optimization of processes of microwave heating.

Students' involvement in the work of the Group is valuable. Undergraduates participate in carrying out projects while fulfilling the requirements for a degree. Graduate students work as research assistants and contribute to computations and interaction with both industry and software vendors. The students learn and use the software (including the commercial one) in order to master the packages for specific needs of the designers and users of microwave equipment and ovens. Those who would then decide to enter the industry would bring with them their knowledge.

The Group benefits from the excellent computing facilities of WPI, called in 1998 by the *Yahoo! Journal* one of America's 10 Most Wired Colleges. In July 1999, the IMMG received the endorsement of IMPI.

For more information about the CIMS/IMMG, please contact Vadim V. Yakovlev at vadim@wpi.edu, tel.: (508) 831 5495, fax: (508) 831 5824.

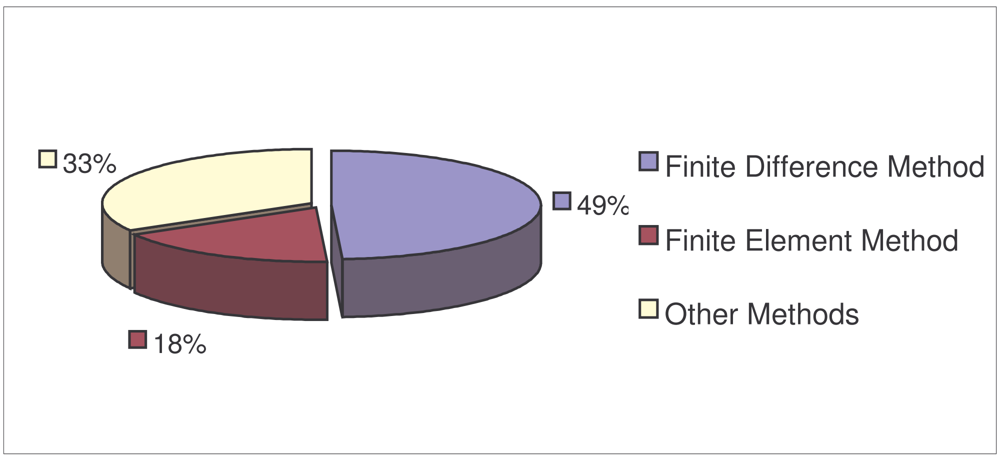


Fig. 1. Popularity of numerical methods in microwave power research in 1996-1998.

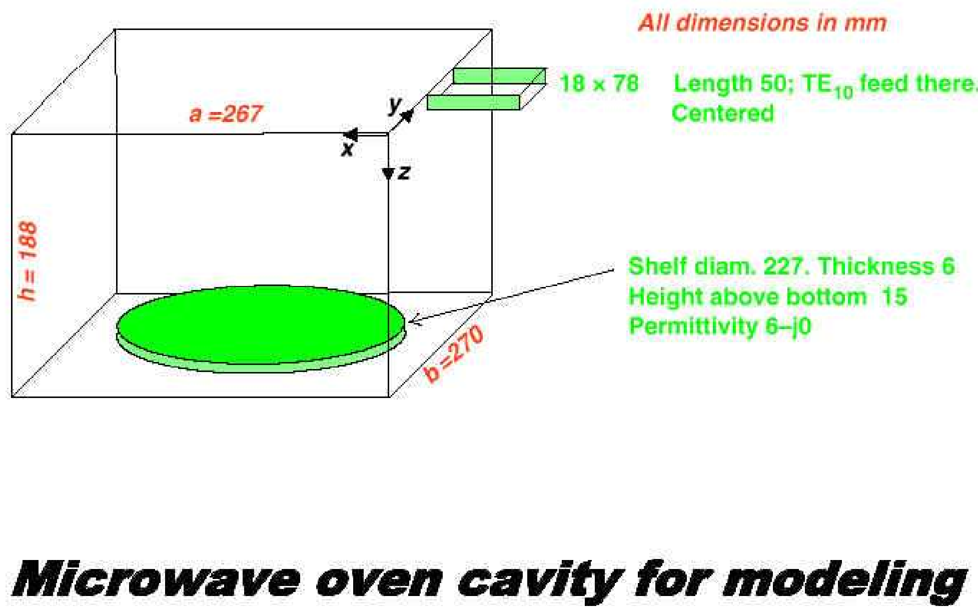
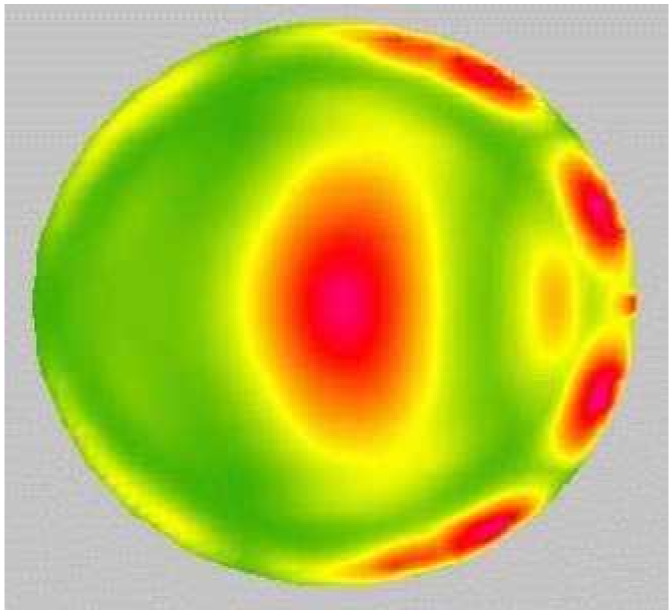
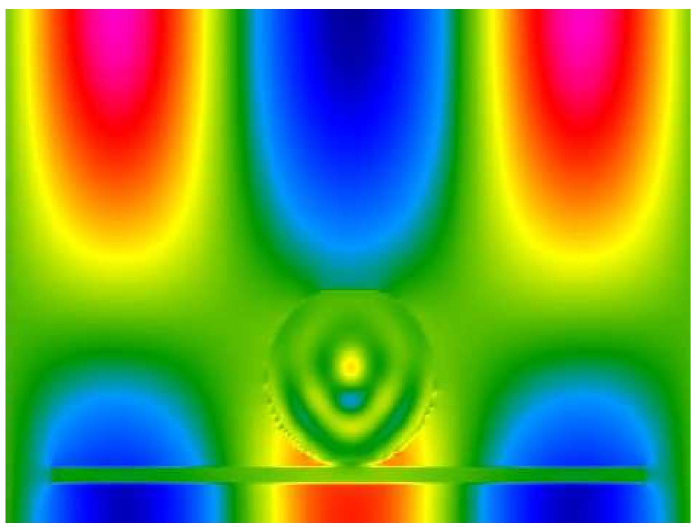


Fig. 2. The QW3D typical image: a microwave oven with a two-layered pizza on a susceptors.



(a)



(b)

Fig. 3. Examples of computation by QW3D [6]: the heating pattern in a susceptors under a two-layered pizza (a); the electric field in the vertical plane of the cavity through the center of a spherical potato (60-*i*16) lying on a non-rotating turntable (b)

Table 1. Commercial EM Packages for Microwave Power Engineering[6]

Vendor	Package	Platform
Ansoft, Corp. www.ansoft.com	Ansof HFSS, EMAS	UNIX, Windows 95/98
ANSYS, Inc. www.ansys.com	ANSYS/Emag	UNIX, Windows 95/98
CST GmbH www.cst.de	MAFIA 4	UNIX, Windows 95/98
Electro Magnetic Applications, Inc. www.sni.net/~emaden	EMA3D	UNIX, Windows NT
HP Eesof www.tmo.hp.com/tmo/hpeesof/	HFFS 5.4	UNIX, Windows 95/98, NT
Infolytica, Corp. www.infolytica.com	FullWave	UNIX, Windows 95/98, NT
Remcom, Inc. www.remcom.com	XFDTD 5.0	UNIX, Windows 95/98, NT
Sonnet Software, Inc. sonnetusa.com	KCC Micro-Strips	UNIX, Windows 95/98, NT
QWED s.c. www.qwed.com.pl	QW3D 1.8	UNIX, Windows 95/98, NT
Vector Fields, Inc. www.vectorfields.com	SOPRANO SS/EV	UNIX, Windows 9598, NT
Weidingler Associates, Inc. www.wai.com	EMFlex	UNIX
Zealand Software, Inc. www.zealand.com	FIDELITY 2.0	Windows 95/98, NT

[6] Adapted and updated from [4]