Paper

FDTD modeling and experimental verification of electromagnetic power dissipated in domestic microwave ovens

Paweł Kopyt and Małgorzata Celuch-Marcysiak

Abstract — The FDTD (Finite Difference Time Domain) method has proven to be effective in modeling high-frequency electromagnetic problems in telecommunications industry. Recently it has been successfully applied in microwave power engineering. In order to accurately model scenarios typical in this field one has to deal with the movement of objects placed inside cavities. This paper describes a simple algorithm that makes it possible to take into account object rotation – important in simulations of domestic microwave ovens. Results of example simulations are presented and an experimental verification of the simulation tool is performed.

Keywords* — *electromagnetic simulations, FDTD algorithm, microwave heating.

1. Introduction

Microwave power engineering community has only recently discovered the FDTD and other modeling methods successfully used in telecommunications for years. Like in any other field, also in this application modeling is very beneficial as it cuts down the design costs. In the literature one can find various approaches to model heating devices. The general possibilities and limitations were described in [1]. In [4] the authors used FDTD to model microwave power distribution in a food object placed inside a microwave oven. Simulations and optimisation results of power uniformity in objects passing through a tunnel industrial oven have been presented in [2].

One important feature has been so far overlooked. In real-life heating devices the greater uniformity of power distribution inside the heated objects is often achieved with the object movement inside the cavity while heating is on. In industrial ovens the foodstuffs are simply passing through a cavity on a conveyor belt [2], while in small-scale simpler devices – like domestic microwave oven – the object is placed on a rotating shelf.

The accurate modeling of microwave heating scenarios requires that movement of the objects be taken into account. This paper introduces a simple but effective method to conduct an accurate modeling of an object heated inside a domestic microwave oven with the object rotation. The algorithm itself is presented in Section 2. Section 3 describes various power uniformity criteria. One of those presented is chosen for further use. Section 4 presents the results of simulations and comparison of the introduced method with results obtained without its application. Section 5 discusses comparisons of the FDTD simulations with real-life measurements.

2. Method of simulation

The basic electromagnetic simulation software has been developed for years and currently on the market one can find ready packages of proven reliability and accuracy, successfully used in various problems. Especially, the software based on FDTD method has proven advantageous over other solutions employing FEM method [2]. One of those – QuickWave 3D developed by QWED – with implemented conformal FDTD method [5, 6] is known in microwave power industry. Several papers presenting results obtained with its help have been published and it ranks high on the list of available software suited for microwave power simulation [7].

An additional feature makes it even more suitable to the task – the possibility to define scenario geometry using parametrized macros in the so-called UDO language. This feature together with the possibility to define scripts (tasker files) instructing QuickWave to dump chosen data at a given moment facilitates effective simulation and optimisation of complex problems. It has been successfully used in [3].

That way of conducting simulation has been adopted in our case. The experiments have been conducted with a model of an example microwave oven. The whole geometry of the model, together with excitation and the sample object being heated, have been prepared with a single macro. By modifying its parameters one can place the sample object at any angle inside the oven. Next, using an external routine written in Matlab [8], one can trigger QuickWave simulation several times, each time for a different object position. Calculated dissipated power pattern in the object cross-section will be different for each angle. It means that by collecting the data on dissipated power for each angle and summing them up one can arrive at more accurate information on how evenly the dissipated power is distributed inside the object during heating and rotation.

Table 1
Relative error of the averaging (for sets 7 and 8 the mirroring was used)

Set number	1	2	3	4	5	6	7	8
Step [°]	5	10	20	30	45	60	*)	**)
No. angles	72	36	18	12	8	6	6	7
Effective no. angles	72	36	18	12	8	6	10	12
Error [%]	0	0.0916	0.3043	1.1609	4.0086	5.1448	1.9044	1.1267

*) Angles in set no. 7: 0°, 36°, 72°, 180°, 216°, 252°.
**) Angles in set no. 8: 0°, 30°, 60°, 90°, 180°, 210°, 240°.

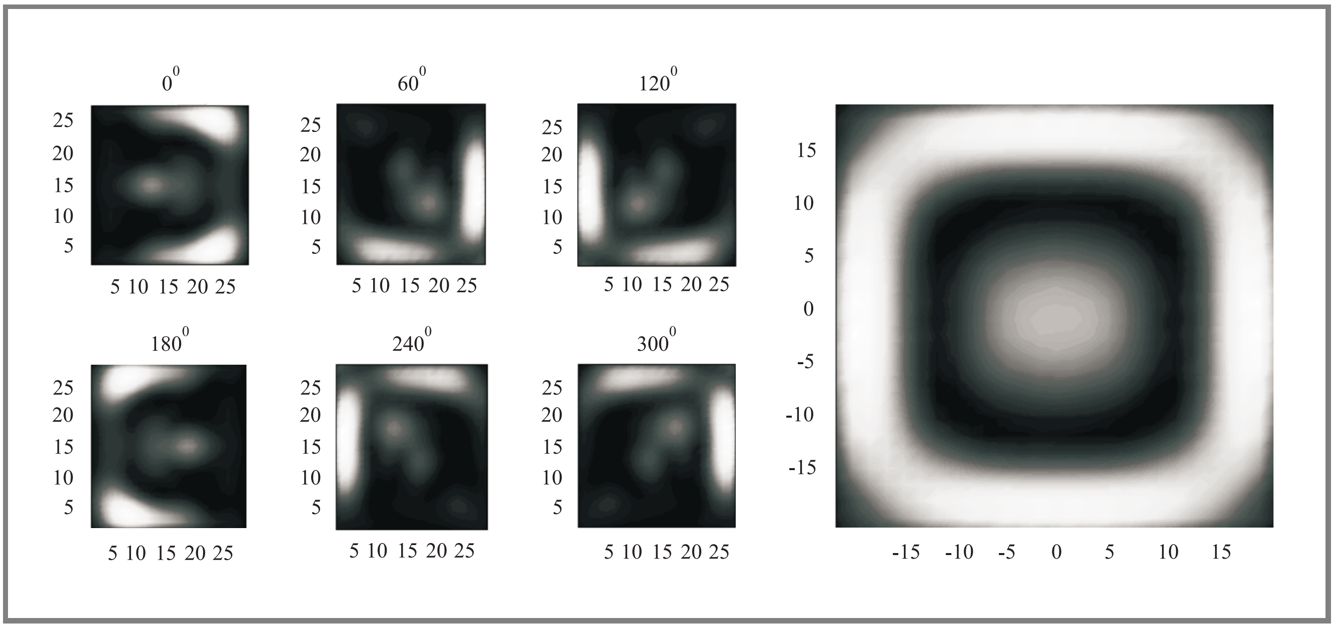

Fig. 1. Dissipated power pattern for six angular positions of the object (from 0 to 300° with the step of 60°).

The FDTD method requires that the model be discretized with small parallelepipeds (or cells). Fields and resulting power distribution are calculated within each such cell. The collected information comes in the form of snapshots of dissipated power in the object's cross-sections. If the object is rotated, the snapshot is rotated as well. Obviously direct summing of the data for different rotation angles is not possible. This task requires that the snapshots of dissipated power be first brought back to their original position – 0 degrees. Since in each case the angle of rotation is known one can achieve this using standard formula for coordinate system rotation applied to each cell:

$$\begin{aligned} x' &= x\cos\alpha + y\sin\alpha\,, \\ y' &= -\sin\alpha + y\cos\alpha\,, \end{aligned} \tag{1}$$

where x, y are coordinates of the cell center of the rotated snapshot, while x' and y' are coordinates of the cell center after the back-rotation.

After the back-rotation it is possible to average the dissipated power for all the angular positions of the object. Figure 1 presents six matrices that have been rotated back and are ready for averaging. During all the experiments the object (a parallelepiped $40 \times 40 \times 20$ mm) has been placed centrally on the shelf and rotated around its center. The object is made of meat modeled as material of relative electric permitivity $\varepsilon = 50 - j20$.

The accuracy of the averaging procedure for different number of distinct positions has been tested. As a reference we have used averaged pattern P^5 obtained by summing up power snapshots taken every 5°. Table 1 contains results of comparison between the reference pattern and patterns based on a smaller number of positions. The relative error values have been obtained with the following formula:

$$e(a) = \frac{\sum_{i=1}^{N}\sum_{j=1}^{M}\left(P_{ij}^{5} - P_{ij}^{a}\right)^2}{NM}\,, \tag{2}$$

where P^a is a pattern whose accuracy we verify against the reference pattern P^5, N and M are the dimensions of the patterns (given in cells).
The error grows as the number of angular positions decreases. There is a way to lower the number of angles without deteriorating the accuracy. We have presented 6 templates in Fig. 1. It is clear that due to the symmetry of the problem one can find pairs of snapshots that are mirrored copies of each other (60° and 300° or 120° and 240°). It is enough to get one result and sum it up twice with and without mirroring. Sets 7 and 8 of data in Table 1 contain angles only from the first and third quarters of the coordinate system, with subsequent mirroring. It is clear that error is low despite the relatively small number of angles, for which the simulations were performed.

3. Power uniformity criteria

Effective comparison of the uniformity of power distribution within different objects requires a carefully chosen criterion. A criterion like that is also necessary in order to conduct an optimization process. We have browsed the available literature and chosen two criteria for further consideration. We have also proposed a new one which seems to be most useful.

- **Differential power difference** – difference between the highest and the lowest value of dissipated power found inside the object (or its cross-section in the case of analyzing the object as a set of two-dimensional layers) [2].
- **Statistical criterion** – standard deviation of the dissipated power distribution normalized by the mean value [4].
- **Integral power criterion** – maximum value of power dissipated in a small volume (surface when we deal with single layers of object) normalized by the total power dissipated in the object (one layer).

The differential power criterion constructed as a simple difference between power dissipated in hottest and coldest spot and used in [2] is not suitable in our case. It takes into account only two points out of many available in object's volume which does not fully describe power distribution in complex two- or three-dimensional geometries.
The statistical criterion seems to be a better choice as all the points (or cells) of the object give contribution to the total value of the criterion. We have conducted some tests of the criterion trying to confirm that it gives results, which agree with intuition. The tests have shown that the criterion cannot be used in our case despite the fact that it has been successfully applied in [3, 4].
The third proposed criterion – the integral power criterion – has been eventually chosen for further experiments. It has been confirmed in tests that it can be treated as accurate description of the power distribution. What is also important is that this criterion is completely based on physical concepts and phenomena (e.g. power dissipated in a specified region) that we want to measure. The criterion is defined with the following formulae:

$$f_p(v) = \max\left(\frac{\int\limits_{S_A(x_0,y_0)} SAR(x,y)\,ds}{\int\limits_{S} SAR(x,y)\,ds}\right), \tag{3}$$

$$f_p(v) = \max\left(\frac{\int\limits_{S_A(x_0,y_0)} -SAR(x,y) + 2E\big(SAR(x,y)\big)\,ds}{\int\limits_{S} SAR(x,y)\,ds}\right), \tag{4}$$

where S is the area of the object's cross-section (if whole volume of the object is taken into account then the integral is calculated over the volume), S_A is the small fraction of the whole area of the object's cross-section, SAR is function describing the distribution of the specific absorption rate (in reality it is discretized due to the nature of the applied simulation method) and E is the symbol of calculating expected value.
It also has one important advantage – it allows taking into consideration not only the value of power dissipated in cold (or hot) spots but also the shape of the power distribution. A sharp peak in power over a small region is not so important as a peak similar in value but spread over a larger region. The tuning of the criterion means changing the S_A area. If it is small in comparison to S then the criterion is tuned to sharp peaks. By making the S_A larger we average the value of power peaks over greater area thus making the influence of such peaks smaller.
There is also another advantage of the integral power criterion. A typical goal of the optimization process is a uniform power distribution within the heated object. Yet from a practical viewpoint, this is usually a secondary goal as it is more important to assure that in the volume of the heated object none of the regions will be heated too much (hot spots elimination) or all the regions' temperature will be high enough (cold spots elimination) to kill pathogens. One can easily modify the criterion for each case. The (3) criterion is to be used in hot spot elimination while (4) should be used to eliminate cold spots. The modification in (4) is simply turning the power distribution around its mean value. Thus all the peaks become valleys and all the valleys (or cold spots) are peaks which the optimization algorithm will try to eliminate.

4. Results of simulation

Using the algorithm described in Section 2 together with the integral power criterion presented in Section 3 two numerical experiments have been conducted. The results show that taking into account the object rotation can change the resulting dissipated power distribution in heated objects, and consequently the optimum object design.

The experiments have been performed with a modified domestic microwave oven model. On the shelf a sample object has been placed whose shape can be modified with a single parameter. In order to maintain simplicity of the experiments and keep the computation time reasonably short the object's shape can be changed by rounding its corners. The parameter is defined with the following formula:

$$n = \frac{r_c}{0.5a}, \tag{5}$$

where r_c is the radius of the curvature of the object's corners while a is the length of the object's side (the assumption is that the object is equilateral). One can easily introduce other parameters (e.g. ratio of the object's sides). Two example objects of different shapes are presented in Fig. 2.

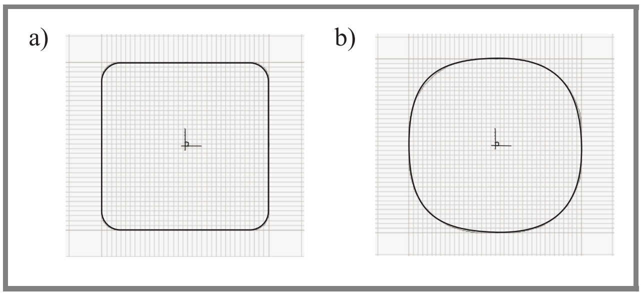

Fig. 2. Two example objects: (a) $n = 0.2$; (b) $n = 0.8$.

The sample object used in the experiments has been made of meat (material density is 1 g/cm^3), its volume has been 300 cm^3, its height – 20 mm. The experiment goal has been to average dissipated power over 6 angles (angle set 7 listed in Table 1) in the plane cutting the sample object at the level of 2, 10 and 18 mm from its base. Then the integral power criterion has been used to calculate the uniformity of the distribution in each layer. The calculations have been repeated for different shapes of the object (different values of n parameter in Eq. (5)). The results are presented in Fig. 3 together with similar data obtained by calculating the uniformity of power distribution for one angle only (0°).

Clearly the object rotation contributes to higher heating uniformity. It is also important that object rotation makes the power distribution less sensitive to the shape of the heated object. From Fig. 3 one can see that when the object rotation has been taken into account, the shape factor influences the uniformity to a much lesser extent as compared to the case in which the rotation has not been employed. Without rotation, we observe one local minimum at $n = 0.8$ and a global minimum at $n = 0.1$.

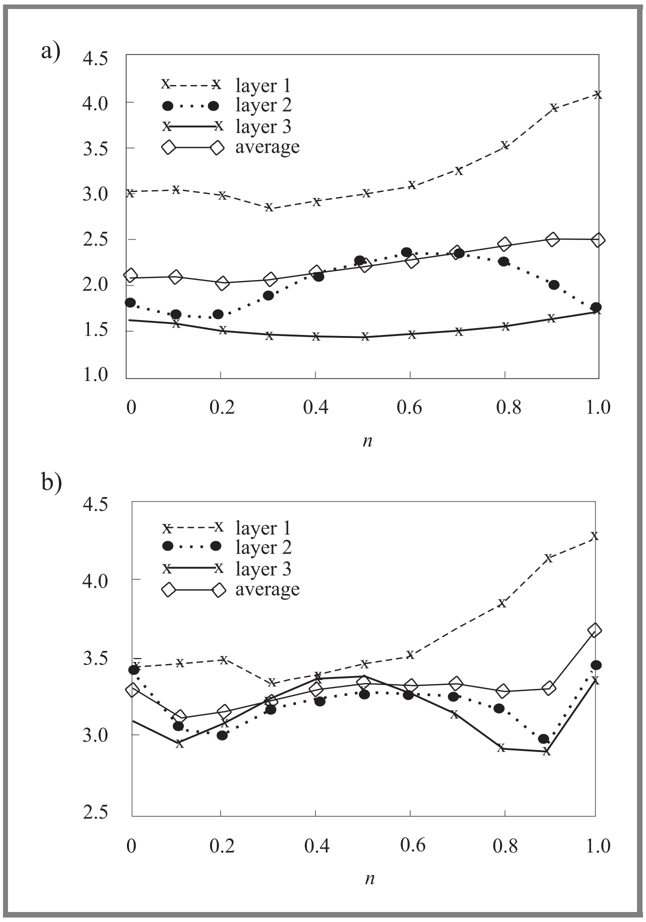

Fig. 3. Comparison of the uniformity (integral power criterion) of dissipated power distribution with (a) object rotation; (b) without rotation.

With rotation, the local minimum disappears, and the global one shifts to $n = 0.2$. This means that the optimum design of a food package would be different in the two cases.

5. Experimental validation of the accuracy of simulation

The accuracy of the simulation software employed to obtain the results described in the previous section has been verified experimentally. The measurement equipment recently acquired by the Institute of Radioelectronics has been employed in the task and presented in Fig. 4. It consists of a microwave oven (by Plazmatronika, www.plazmatronika.pl) with adjustable power level controlled with a PC, and a signal conditioner with set of eight thermometers (by Fiso Systems, www.fiso.com) that can register temperature changes simultaneously.

A set of temperature measurements has been conducted. A sample of bread 60(w) × 60(d) × 20(h) mm has been

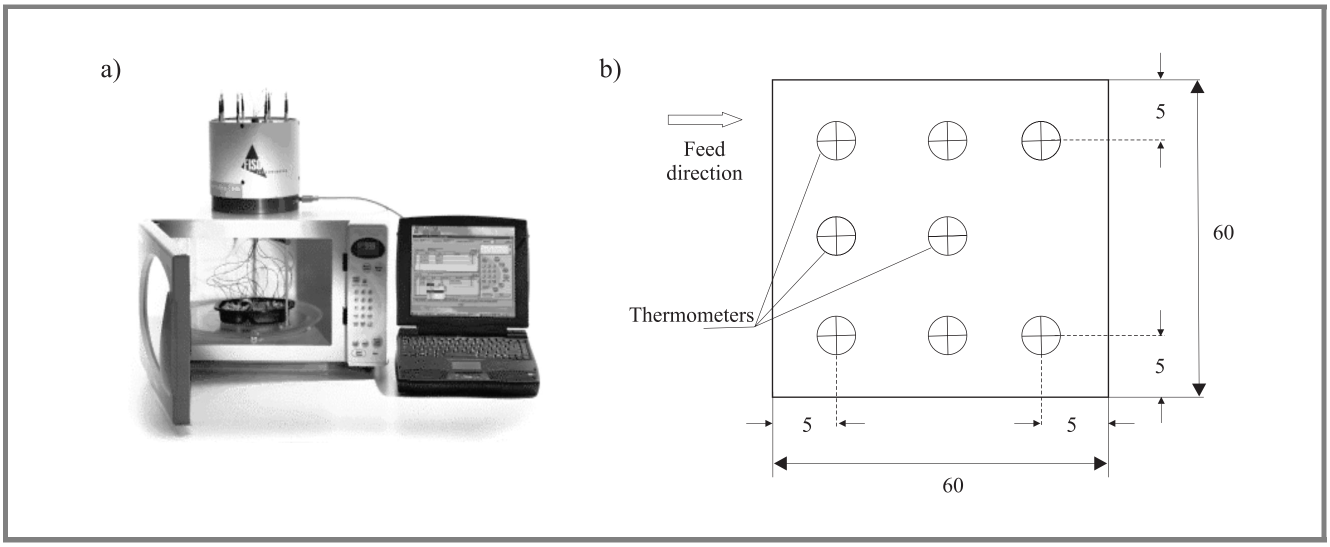

Fig. 4. Measurement system used in verification of the simulation results (a); placement of thermometers in sample (b).

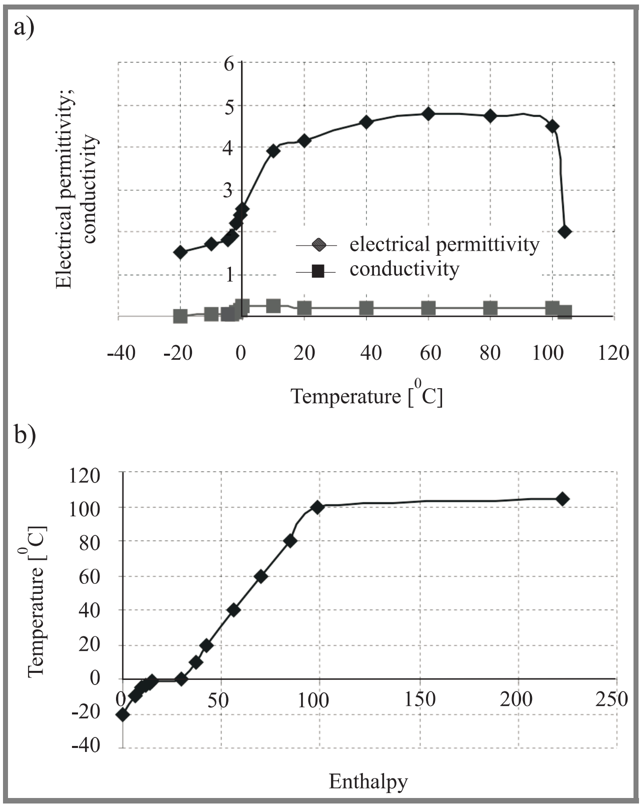

Fig. 5. Data contained in the file describing the media: (a) dependence of the relative electrical permittivity and conductivity [S/m] on the temperature; (b) dependence of the temperature in a cell on the enthalpy in this cell.

placed centrally on the oven turntable. The power level has been set to 100 W and the heating lasted around 5 minutes. Temperature has been registered at 8 locations shown in Fig. 4b, in the middle layer of the sample. Since the main goal of the experiment has been to check the accuracy of the software, we have performed the heating without sample rotation. It has made the computation time much shorter as there has been no need for repeated simulations of the oven with sample at various angular positions.

After the measurements the computer model of the microwave oven has been prepared and a set of simulation results obtained. An additional module – called BHM (basic heating module) [9] – has been used that takes into account the temperature-induced changes of the media parameters. The changes are based on the data stored in an external file containing enthalpy and corresponding media parameters: electrical permittivity, conductivity (losses) as well as temperature. The data stored in the file used in the bread simulation have been presented in Fig. 5.

The BHM module repetitively modifies the media parameters according to the dissipated power and data provided in the file. The total heating time has to be divided into smaller timesteps in order to accurately model the gradual changes of the media parameters. The operations performed in each step have been illustrated in Fig. 6. First, the steady-state needs to be reached in order to calculate the dissipated power envelope in the simulated circuit. Then the lossy materials are being heated for the time equal to the timestep length. After the heating has been done the enthalpy is obtained and the media parameters are modified according to the file, and temperature in each cell is changed.

The comparison of the experimentsal data and the simulation results has been presented in Fig. 7a. The comparison has been made in the hot spot which is just off the sample center. The curves are close to each other with the biggest discrepancy occuring at the beginning of heating process. This can be ascribed to the inertia of the thermometer. The

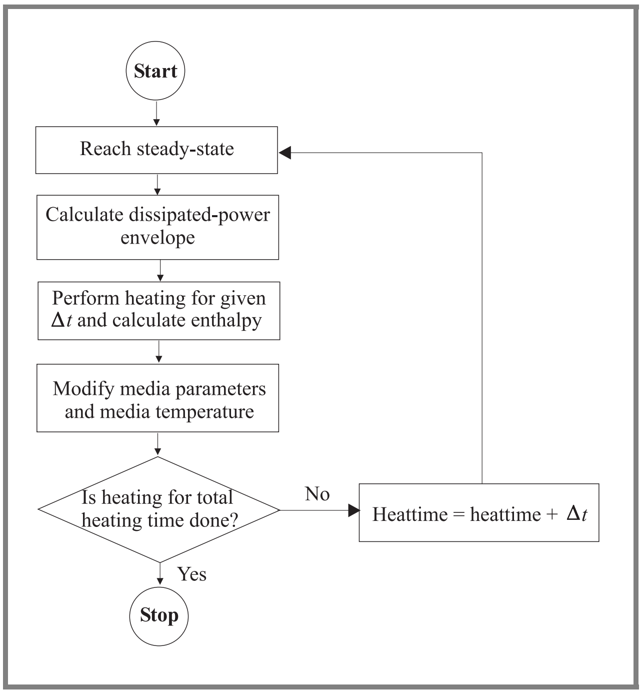

Fig. 6. Operation of the BHM module.

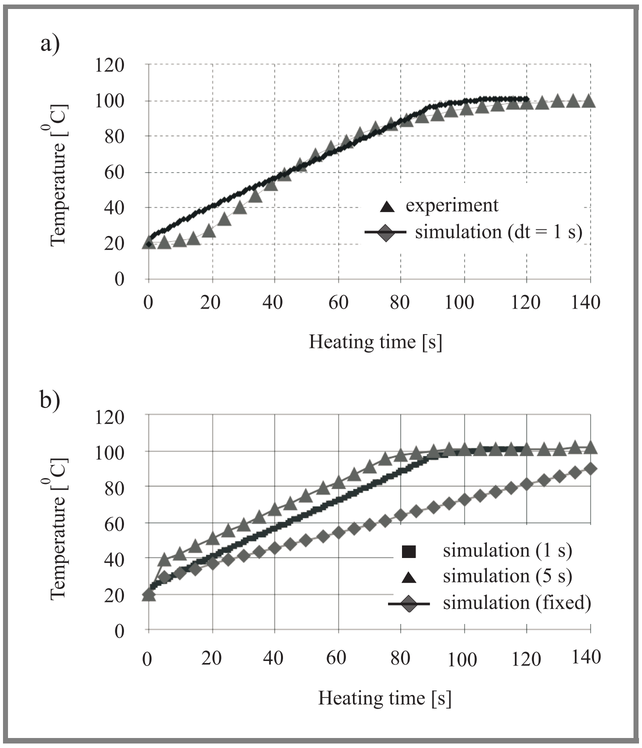

Fig. 7. (a) Comparison of the measurements and the simulation data (in the hot spot); (b) comparison of simulation results (two cases where media parameters where modified with two different heating timesteps – 1 s and 5 s – and one case where media parameters stayed unchanged).

simulation data have been obtained for a heating time step set to 1 s. It has been checked that in this case bigger values can lead to inaccurate data.

The inertia of the thermometers used in the measurements has been checked experimentally. The thermometer has been placed first in a glass filled with water of room temperature (25°C) and then transferred to a glass filled with much hotter water. The output has been registered and we have shown it in Fig. 8. It seems that in case of water the time for the temperature to rise to the correct level is around 4 s. In case of water the contact resistance between the thermometer and the medium is not high. With bread the resistance is much higher so greater inertia can be expected.

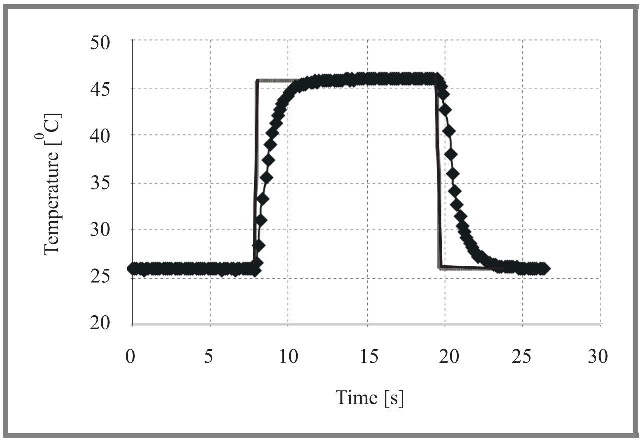

Fig. 8. Response of the thermometer used in experiment (water).

The timestep of the heating is an important factor since choosing too small values will lead to excessively long computation time without any improvement in accuracy. Too big timestep, though, is even more dangerous as it may cause abrupt changes in temperature and, in turn, jumps of the media parameter values which can bring instabilities into the simulations. The data obtained for different timestep values are presented in Fig. 7b. They have been compared with the data obtained without any modification of parameters.

6. Conclusion

We have presented an effective and simple approach to modeling of problems with load rotation, which is an important issue in microwave power applications and has not been previously addressed. It is a post-processing method that is easy to implement with standard mathematical routines found in e.g. Matlab package. We have also considered a couple of examples proving that object rotation may change the dissipated power distribution within the object, and hence optimum geometry of the heating system. This is important in design of microwave ovens and microwaveable food packages. The experimental verification of the simulation tool has been conducted and it has been shown that the accuracy of the computations is high enough to ensure a good agreement with measurements.

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Paweł Kopyt was born in Warsaw, Poland, on May 15, 1975. He graduated *cum laude* in telecommunications from Warsaw University of Technology, where he received an M.Sc. degree in 2001. At present, he is a Ph.D. student at Institute of Radioelectronics, Warsaw University of Technology. Among his interests are numerical techniques for simulation of electromagnetic and thermal fields and microwave heating.

e-mail: pkopyt@elka.pw.edu.pl
Institute of Radioelectronics
Warsaw University of Technology
Nowowiejska st 15/19
00-655 Warsaw, Poland

Małgorzata Celuch-Marcysiak is an Assistant Professor at the Warsaw University of Technology and Vice-President of QWED company. She received an International Baccalaureate from the United World College of the Atlantic, in 1983, M.Sc. and Ph.D. in electronic engineering from Warsaw University of Technology in 1988 and 1996, respectively. She is one of the main authors of QuickWave electromagnetic simulation software. She contributed to more than 60 technical publications. Her main professional interest is in numerical modeling of electromagnetic problems.

e-mail: m.celuch@ire.pw.edu.pl
Institute of Radioelectronics
Warsaw University of Technology
Nowowiejska st 15/19
00-655 Warsaw, Poland