EXPERIMENTAL VALIDATION OF NUMERICAL ANALYSIS AND OPTIMIZATION OF HOUSEHOLD MICROWAVE OVENS

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Abstract: *Electromagnetic and thermal computer simulation is mandatory for the optimization of the design of microwave oven and for the evaluation of temperature distribution in the food. Numerical results are usually different from the experimental ones and this can be due to a too much simplified model or to a wrong choice of the test load.*

In the present paper an accurate numerical model, including electromagnetic and thermal simulation, taking into account the rotation of the turntable, is presented and discuss.

The thermal measurements have been done in a particular material made by agar and water: its thermal and dielectric properties are similar to water, but the load is a solid one.

Keywords: Coupled electromagnetic and thermal problems, microwave oven simulations, innovative solid test load.

INTRODUCTION

In the evaluation of efficiency for household microwave oven the standards [1] take into account the increasing of temperature of 10 °C (from 10°C to 20°C) in a particular water load (1 litre), this resulting in a only one typical use of it. Moreover, about thermal uniformity inside the food, the standard consider a load which shape is a grid of rectangular samples made of water: it is so oriented to guarantee the maximum efficiency under this point of view, nothing considering about the shape and size of real common food.

Some strands of thought about MWO improving are oriented to find some solutions (i.e. position of food or tuning of the device) in order to optimize the efficiency by reducing reflected power [2]; however, this approach does not consider temperature distribution inside the food (at least, one measurement point is taken into account [3]).

Some new ideas on evaluate the performance of a microwave oven (considering not only the energy efficiency, but also temperature distribution) can be considered if we are able to evaluate the temperature distribution inside the food.

Of course, it’s rather difficult to foresee the exact temperature distribution, because the only way to know it is using numerical analysis and this usually gives results different from the experimental ones: this can be due, i.e. to a too simplified numerical model or to wrong choice of the test load.

Anyway, most recent software and powerful workstations allow to create very accurate numerical models, including electromagnetic and thermal problems solution and also taking into account the rotation of the turntable, giving the possibility to simulate a realistic use of the device: results can be obtained in a very reasonable time.

The first step of a typical numerical approach is to calibrate the models. For this reason thermal measurements on a particular material made by agar (2%) and water (98%) have been performed: the thermal and dielectric properties of agar are very similar to water, but it has the consistency of a gel, this allowing us to use different approaches for measurements.

Using this load, in fact, it is possible to perform several thermocouples measurements (accurate both in position and in amplitude) and to combine them with results obtained by an infrared camera in order to have a good mapping of temperature distribution inside different loads (both in volume and in shape).

In the following, both numerical and experimental results will be presented in order to validate the numerical models; then we’ll discuss on different proposal for the optimization of the actual microwave ovens.

THEORETICAL BACKGROUND

Influence of food geometry and dielectric properties on microwave heating performances

The absorption of microwave energy in foods is dependent on both the electromagnetic fields and the microwave penetration pattern in the food material. The field distribution is in turn strongly influenced both by the type of cavity, the waveguide system, as well as by the type, shape and distribution of the food inside the oven.

E*dges and corners overheating*

A sample with sharp edges and corners which is microwave heated will show field energy concentration there, which cause selective heating. Briefly described, a sharp edge or corner will act as an antenna and attract more energy than the surrounding areas.

At the boundary between the load and the surrounding air, one of the boundary conditions in the solution of the electromagnetic problem leads to the continuity condition of the parallel component of the electric field. Edge overheating is strongly influenced by the polarisation and incident angle of the incident field, the angle and the curvature of the edges, the permittivity of the heated food materials and the presence of other scatterers close to the edge.

At the food edges, microwaves approach the food from two different directions. Furthermore, parallel to the surface at the boundary, the electric fields have two polarisations. The resulting concentration of the energy distribution to the sharp edges is explained by the continuity condition at the boundaries of the parallel electric fields.

Concentration heating effects

Considering microwave heating as electromagnetic waves which may be reflected, absorbed or refracted, it can be seen that a certain amount of the energy is reflected at the food surface, and on the other hand some energy is refracted. Part of the refracted energy will be absorbed. Most of the remaining energy will be reflected back at the other food surface and so on. Depending on the food geometry, the result can be focusing of energy to certain areas, which may be part of the explanation for the so called *concentration heating effects*.

For the cylindrical geometries or similar, such concentration effects can cause concentration of energy in the centre of the food, depending however on both the food diameter and the dielectric properties of it. This centre overheating effect occurs for diameters of approximately one to three times the penetration depth in the material. The effect will be stronger for foods with high permittivity values. At 2450 MHz centre heating usually happens at diameters between 25 and 55 mm.

MATERIAL AND METHODS

Sample of Agar Gel

Agar gel is a dried hydrophilic, colloidal material extracted from various species of red algae. When the Agar's powder is suspended in water and heated to 212°F (100°C), it dissolves. If it is allowed to cool to 110°F (43°C) the medium becomes a solid gel.

The main use of Agar gel is done in biomedical applications, as culture media for bacteria and other microorganisms, in making emulsions, and as a supporting medium for immune-diffusion and immune-electrophoresis.

Nevertheless, Agar gel presents also interesting aspects for microwave heating applications: its physical properties (electrical and thermal) are very similar to water ones. The advantage to use Agar gel consists in its semi-solid constitution, which allows an easier analysis of temperature distribution inside the sample, instead of considering the convective effect of a liquid as water.
In particular, using a IR camera or thermocouples, it is possible to verify a true temperature distribution instead of an averaged value, which loses some important information as the heating uniformity.

In the models presented in this paper, it is very important to know accurately the load's physical parameters. Errors in estimation of dielectric properties of Agar gel, could lead us to analyze distribution of heat sources in the load very different if compared with real ones.

For this purpose, some measurements have been done in order to define Agar gel dielectric properties, concentrate at 2% (2% Agar - 98% Tap water), with measure method of coaxial cable.

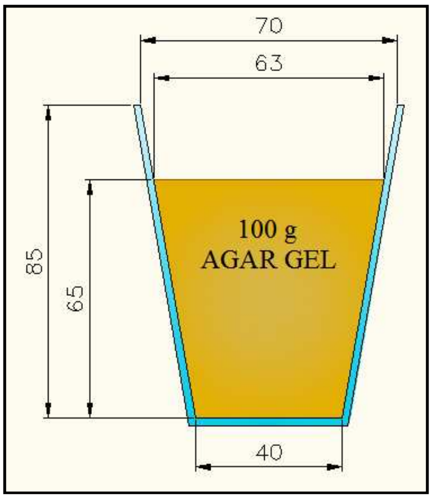
Results are shown in Table 1.

Table 1 – Agar gel (2%) dielectric properties measured

Frequency [GHz]	10 °C		18 °C		30 °C		40 °C		50 °C	
	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''
2,40	77,7	15,1	76,8	14,3	68,3	11,5	72,1	11,1	71,9	11,3
2,41	77,7	15,2	76,8	14,3	68,3	11,6	72,1	11,1	71,9	11,3
2,42	77,6	15,3	76,7	14,4	68,2	11,6	72,1	11,1	71,9	11,4
2,43	77,6	15,3	76,6	14,4	68,2	11,6	72,1	11,1	71,9	11,4
2,44	77,5	15,4	76,6	14,5	68,1	11,7	72,0	11,2	71,8	11,4
2,45	77,5	15,4	76,6	14,5	68,0	11,7	72,0	11,2	71,8	11,4
2,46	77,4	15,5	76,5	14,6	68,0	11,7	71,9	11,2	71,7	11,5
2,47	77,4	15,5	76,4	14,6	67,9	11,7	71,9	11,2	71,7	11,4
2,48	77,4	15,5	76,4	14,6	67,9	11,8	71,9	11,2	71,7	11,5
2,49	77,4	15,6	76,4	14,6	67,9	11,8	71,9	11,2	71,7	11,5
2,50	77,4	15,6	76,4	14,7	67,9	11,8	71,9	11,3	71,7	11,5

The sample used is in accordance with standard IEC 60705 (2006), even if it is upside down in order to have a more stable position for the test's managing.

Figure 1 – (a) Geometrical dimension [mm] of the sample and (b) picture of real load



(a)

(b)

Experimental tests

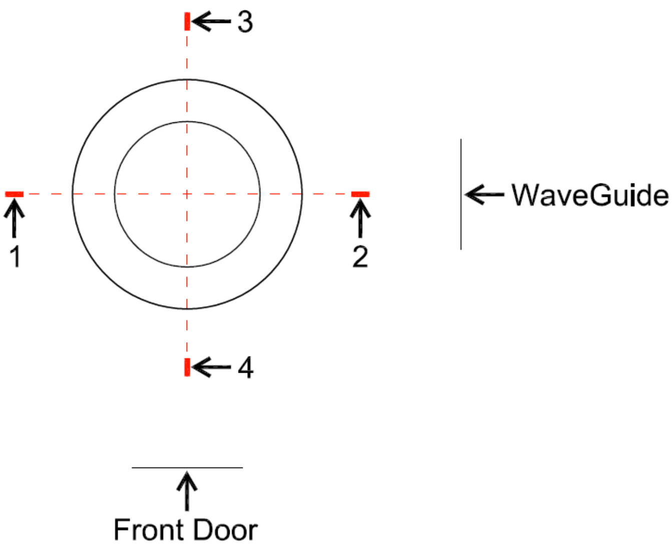
The experimental work has been developed using the following equipment:
1 - Microwave oven with 1 outlet port from waveguide, dimensions: 290Wx290Dx149H (mm), maximum power source: 800W, rotating velocity: 6 rpm
2 - IR camera, in order to capture pictures of temperature distribution, calibrated with emissivity of Agar gel (0,85) using thermocouple as reference.
3 - Sample of Agar gel 2%, located in the centre of the turntable.

Figure 2 – Equipment of experimental tests

The heating process time is 30 seconds, equal to 5 complete rotation of the turntable.

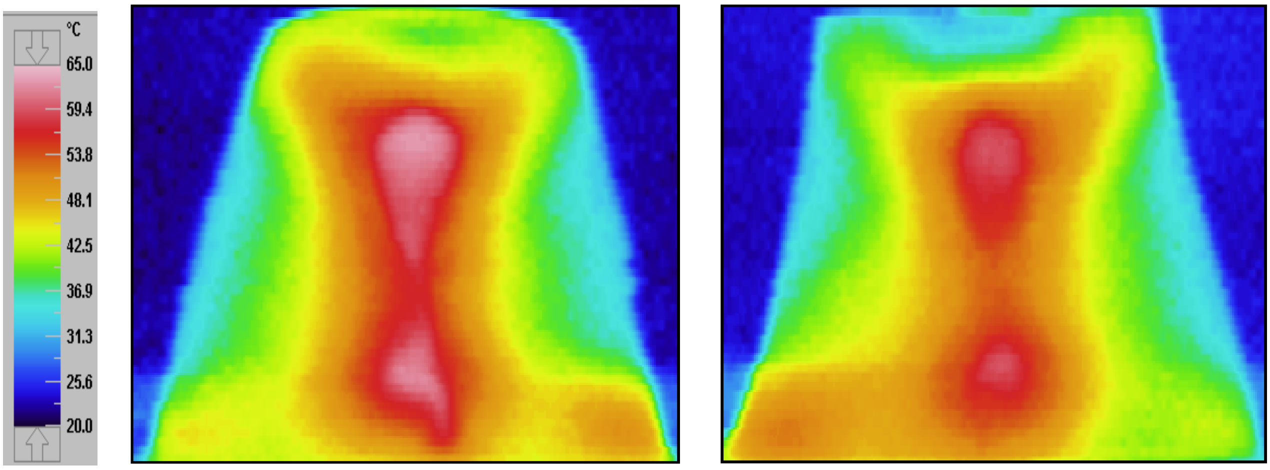
After the heating, the load has been taken off from the cavity and cut across the sections 1-2 or 3-4 (see picture 3) within 30 seconds. The IR thermal camera was already positioned and a picture of the temperature distribution was captured.

Figure 3 – Sections of the sample for temperature analysis



The following figures show the results of the experimental work.

Figure 4 – Results of experimental test – (a) section 1-2 and (b) section 3-4



(a) **(b)**

The temperature distribution shows a non-uniform heating, with a concentration of heat sources mainly in the central part and in correspondence of the upper and lower corners, assuming a configuration similar to a cross.

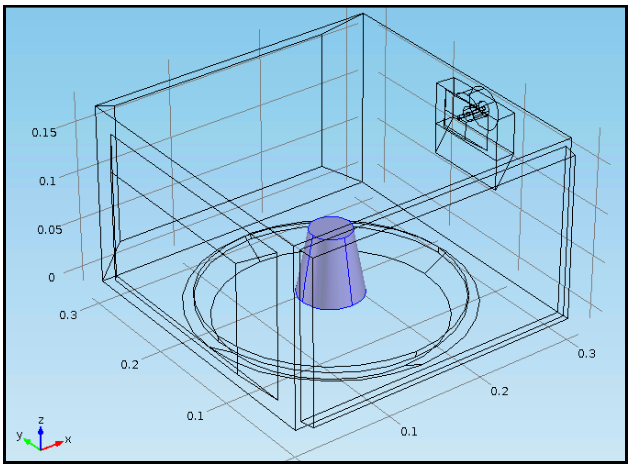
Numerical models

Nowadays numerical simulations are the principal solutions in order to investigate microwave heating problems and designing of optimal devices for consumers market, which quickly require ever more efficient ovens.

In order to validate a numerical model, which should reproduce the physical process as accurate as possible, the software Comsol Multiphysics has been chosen, thanks to the possibility to consider not only electromagnetic problems, but also thermal phenomena and the load's rotation.

Comsol Multiphysics is developed with a FEM method and for this work a 3D full model of the oven has been developed, as shown in the figure 5.

Figure 5 – Model of the oven

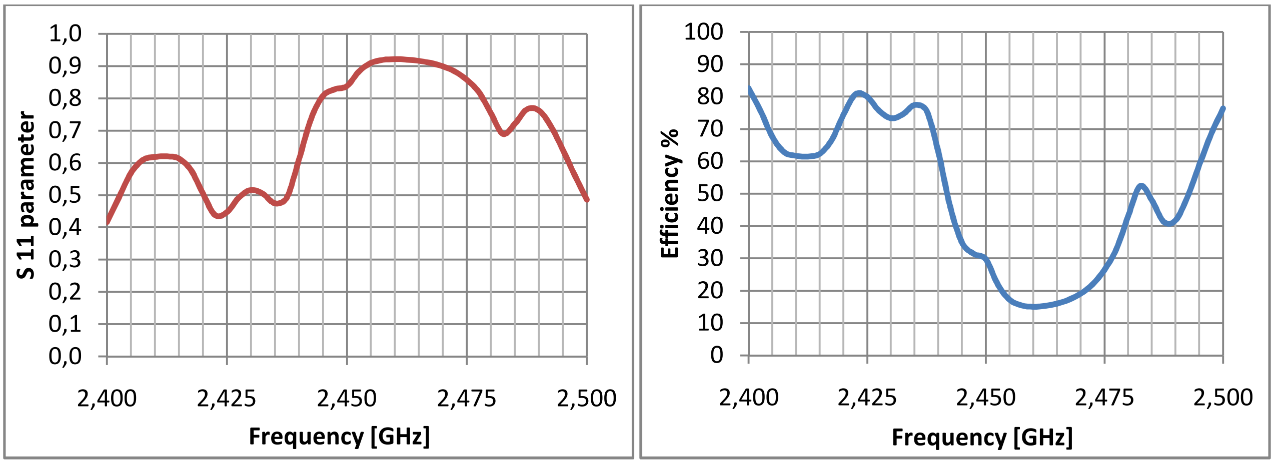


For this application, the following module coupled [6] has been used:

- *"Electromagnetic waves"*: PEC conditions on the walls and coaxial cable feeding.
- *"Heat transfer"*: thermal conduction inside the sample; on the surfaces a heat transfer by convection with the surrounding air has been considered (coefficient equal to 5 $W/m^2 K$).
- *"Live Link for Matlab"*: self-made routine in order to apply the rotation of the turntable.

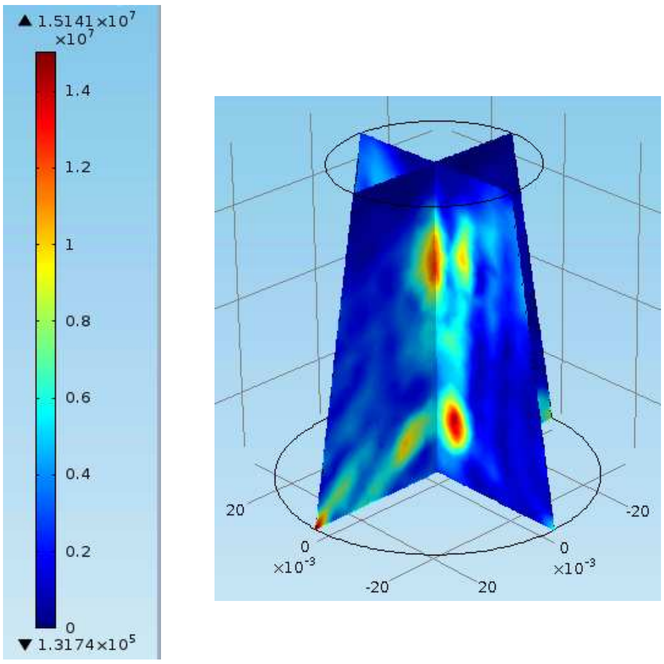
Firstly a frequency domain scan has been developed, in order to investigate the behaviour of the system depending on the frequency. The range of investigation between 2.4 and 2.5 GHz has been chosen, according with the performances allowed from the international standard.

Figure 6 – Evaluation of power reflected: S11 parameter and efficiency



The assumption of magnetron operating on optimum working point has been done (2,4825 GHz for this oven and case). The distribution of heat sources within the load is illustrated in figure 7.

Figure 7 – Heat sources (W/m^3) in the load



Thermal parameters of the sample are [4] :

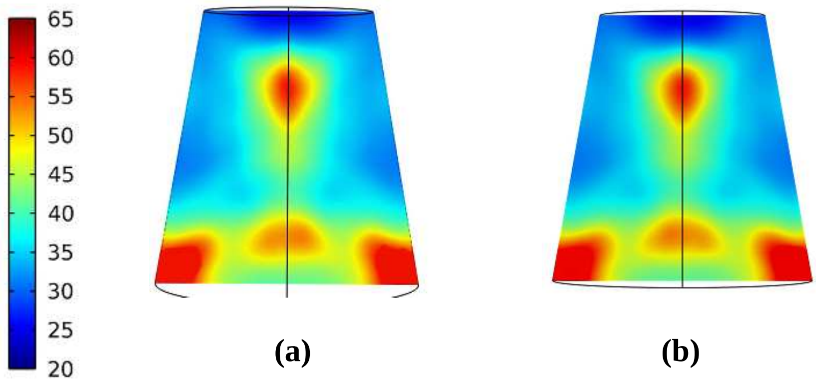
- Heat Capacity : 4200 J/kg K
- Thermal conductivity: 0,60 W/m K
- Density: 1070 kg/m^3

The thermal process is develop using this fixed heat distribution and the rotating load (update of temperature during the rotation).

The simulation is stopped after 30 seconds of heating process.

The results on both the sections 1-2 and 3-4 are represented below.

Figure 8 – Temperature distribution of numerical model: (a) section 1-2 - (b) section 3-4



(a) **(b)**

Comparison of results:

The results of the simulations are quite in accordance with the experimental tests.

The absolute values of temperature and the distribution obtained with the numerical model are very similar compared with the experimental ones, with a general relative error lower than 10%. For the state of art and the household applications we may assume that it is enough accurate. There is only one zone, the lower part of the sample near the corners, which is quite different in comparison to the real sample temperature. This is due to a too much simplified model of the load which in the real case has rounded corners instead of sharp corners . From the theory of electromagnetism, it is known that a sharp corner has the behaviour of an antenna, that is why in the numerical results, the corner is overheated .

The temperature distribution in the sample is in accordance with the theoretical background, in fact the load has a conical shape which is quite similar to a cylindrical configuration, in particular regarding the parallelism of the surfaces. Moreover, the centre over heating can be explained with the combination of several electromagnetic waves reflection within the load material, depending on the inclination angle of the surfaces and the permittivity of the heated material.

CONCLUSIONS

In this paper a new approach in evaluating the performance of microwave oven for household application has been considered.

The use of agar gel allows the calibration of an accurate numerical model of the device by means of thermal measurements obtained with an IR camera: in particular, results for a small load are presented.

Numerical analysis is mandatory for the optimization of the device itself with different loads (both in dimension, type and shape), because it can predict both the working frequency and temperature distribution inside the food.

Outlook for subsequent works are investigations about optimization and design of an oven considering the position of the load inside the cavity and the position of the waveguide on the side-wall.

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