Doctoral School on Engineering Sciences
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Extended summary

Tecniche di predizione di riscaldamento a microonde in camera riverberante e verifiche sperimentali

Curriculum: Elettromagnetismo e Bioingegneria

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Abstract. Electromagnetic fields play an important role in treatments in many application fields, for the property of heating objects that they irradiate to. Microwaves can be used by means of opened applicators, to direct the beam in specific and confined points, or in closed environments such as reverberation chambers. The latter are cavities in which waves, entered through an aperture connected to a Magnetron, continuously reflect in the walls and stirrers, mobile panels that change continually the "electromagnetic" features of the chamber. In order to predict the behaviour of the objects that are treated in the reverberation chamber, FDTD (Finite Differences in the Time Domain) method have been used, which allows the solution of Maxwell's equations, describing electromagnetic fields, in a numerical way. With this procedure we assessed the irradiation of wooden panels to use in the realization of interior furnishings with self cleaning finishes, object of the CATACLEAN research project. We took into consideration the behaviour of the overloaded reverberation chamber, which therefore presents a degradation of the uniformity of the power density distribution and hence the heating. Another point considered in this work, with particular reference to the treatment of cultural goods, was the evaluation of the resonance of biological agglomerates of pest species, that could resonate and therefore cause overheating. For this model has been used the exact solution of Maxwell's equations for the problem of scattering of spheres which, unlike the FDTD method, allows the exact calculation of

the field at each point of the studied domain. These situations can be particularly bad for cultural goods treated with microwaves in order to eliminate pests that may be present in them. Finally we extended the study to ellipsoidal models, which are closer shapes to the reality of pest species.

Keywords. Up to five keywords or phrases in alphabetical order, separated by commas.

1 Introduction

Microwaves are a useful mean for heating in various productive sectors for their advantages:

- High efficiency
- High power density
- Controllability of the heating process
- Heating homogeneity
- Short working time
- Safety for personnel and environment
- Energy saving

This work deals with heating through electromagnetic fields with a frequency of 2.45GHz. The heating prediction using simulation techniques allows designing the process parameters to obtain better results.

2 State of the art of the heating

2.1 Physics of the phenomenon

The objects treated with microwaves are heated principally for two reasons:

- Due to currents (or better current density) that flow through the material conductivity
- For polarization currents, i.e. for the friction of the molecules of the mean when they deform due to the electromagnetic field.

these two phenomena are summarized in the value of the imaginary part of the dielectric permittivity, which can be expressed as:

$$\varepsilon_r = \varepsilon' - j\varepsilon'' \tag{1}$$

where ε_r is the relative permittivity of material, ε' is the real part of permittivity that represents the elastic deformation of charges and that they have no part on the heating, while ε'' represents the dielectric losses due to the two reasons mentioned.

2.2 Applicators

The objects to be heated can be exposed to electromagnetic field using two kinds of applicators [1]:

- Closed applicators
- Opened applicators

2.2.1 Closed applicators

Closed applicators are cavities, also known as reverberation chambers, whose dimensions can be much greater than the wavelength of the electromagnetic field. The waves put inside them are reflected by the metallic walls many times. The result is the presence of a electromagnetic field statistically uniform without predominant direction, polarization and phase in each point inside it. The field uniformity is granted also by the presence of stirrers,

reflecting moving panels that change continuously the electromagnetic shape of the chamber.

2.2.2 Opened applicators

Opened applicators are used when:

- Treated items are too big or they can't be moved
- When the treated zone is a part of the item, and is not possible treat the whole object.

They can be of two types:

- Horn applicators
- Patch applicators

The firsts are antennas of considerable dimensions, compared to other types, and are useful for high power. Their characteristics, like efficiency and standing wave ratio are better compared to other types of antennas. The others are made on planar supports, their size is little, are cheaper and are adaptable to the dimensions of the item to be treated. They are not however suitable for use with high power.

3 Typical applications

Microwaves are used in a lot of productive sectors. Follows a non-exhaustive list of applications, chosen among the most commons.

- Treatments of foodstuff like drying, baking, pasteurization, sterilization and disinfestation [2].
- Packaging disinfestation, essentially made of wood, used in international commerce. This is an alternative to fumigation with Methyl bromide, that is dangerous for personnel and environment [3].
- Artwork disinfestation. In this sector, microwave are increasing importance. The disinfestation from pests with microwaves in an application that allows the control and safeguard the artwork integrity bringing the pests over the lethal temperature.
- Industrial sector. There are numerous industrial application fields of microwaves instead of the traditional heating methods, such as rubber vulcanization, treatment of tissues, drying and baking of ceramic, creation of molds for casting wax, chemical processes, neutralization of asbestos [4].

4 Electromagnetic and thermal modeling

4.1 FDTD simulations

Maxwell's equations have a solution only in a limited number of cases. The alternative is to compute solutions in a numerical way with one of several methods. One of these is the FDTD (Finite difference Time domain); with an opportune choice of the points and the time steps [5], the field components E_x, E_y, E_z, H_x, H_y and H_z at each time can computed with a set of algebraic expressions like [6]:

$$E_{x\ i,j,k}^{n+1} = k_1 E_{x\ i,j,k}^{n} + k_2 \left(\frac{H_{z\ i,j+1,k}^{n} - H_{z\ i,j,k}^{n}}{\Delta y} - \frac{H_{y\ i,j,k+1}^{n} - H_{y\ i,j,k}^{n}}{\Delta z} \right) \qquad (2)$$

where n is the time step, i,j and k the position indexes, Δy and Δz the space steps, k_1 and k_2 numeric constants. With these expressions were developed some "C" software inside UNIVPM Departments. The simulations produce files with the Electric field components in each point of the simulation domain.

4.2 Sphere scattering

One interesting scenario, that allows the exact solution of Maxwell's equations, is that of the dielectric sphere immersed in a medium with losses and hit by a plane wave. Gustav Mie was the first to formulate the solution in 1908. With expressions that use the Bessel functions, Henkel functions and Legendre polynomials is possible to calculate the Electric field in each point of the sphere or of the medium around it [7].

4.3 Load effects in reverberation chamber

The chamber's load can be represented by the ACS (Absorbing Cross Section) [8] of the objects inside it, its value can be easily computed from the results of the simulation. The quality factor Q of a reverberation chamber may be related to the reflection coefficient of the walls [9]. The load presence, that lowers the quality factor of the chamber, can be thought, for the purposes of simulation FDTD, with a worsening of reflection of the walls; this leads to a deterioration of the uniformity of the electric field inside due to the decrease of the number of electromagnetic waves present. This results in a decrease in the number of independent positions of the stirrer [10]. For the simulation purposes this can be compared to a bond between waves sets of plane waves and is represented by a new parameter called SPREAD.

4.4 Thermal model

The thermal evaluation of an object irradiated by electromagnetic fields can be made, in numerical way, using the heat equation. In this work was used a commercial software, COMSOL, for this purpose.

5 Cataclean project

CATACLEAN project arises from a collaboration between l'Università Politecnica delle Marche (Ancona, Italy) and the Lipetsk State Technical University (Lipetsk, Russia) to develop a self cleaning catalytic film for furniture panels. Microwaves play an important rule in the fixing the films to the wood panels inside a reverberation chamber. FDTD simulation is based on the analogy between the electromagnetic field in the reverberation chamber and a set of plane waves with random direction, polarization and phase in an open environment [11]. Repeating this process M times it's possible to represent the independent positions of the stirrer. Several sets of wood panels, varying number, size, distance and dielectric characteristics were simulated and was studied their power density

distribution. For example in Figure 1 it's possible to see the power density trend and its standard deviation as function of wood's conductivity.

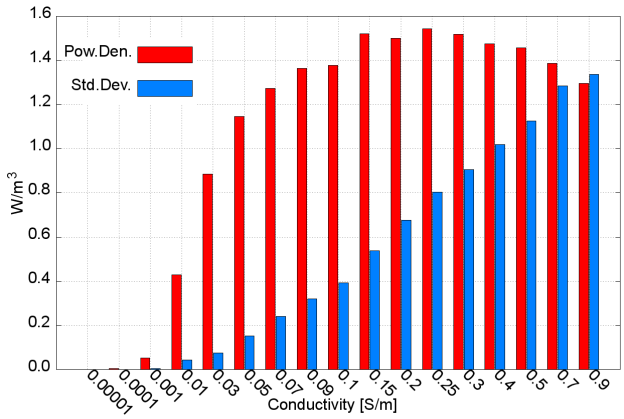

Figure 1. Power density and its standard deviation vs. wood's conductivity.

Another study was made about the value of ACS (Absorbing Cross Section) of load assets and the efficiency of reverberation chamber, for various values of its quality factor (Figure 2)

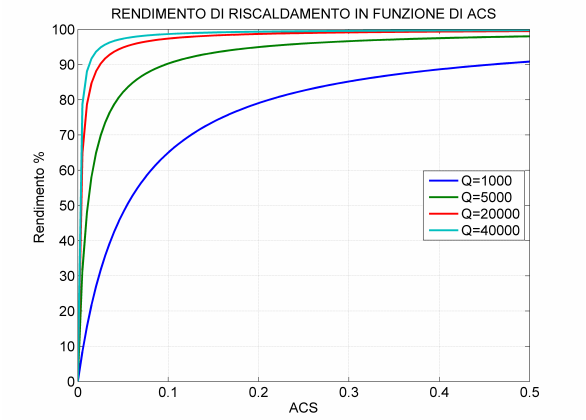

Figure 2. Heating efficiency vs. object's ACS.

Derived values of the wall's reflection coefficient and of SPREAD parameter have been used to verify experimental results using a commercial reverberation chamber obtaining encouraging results.

6 Damage to works of art due to hot-spots

The FDTD simulation can predict the power density distribution in irradiated wooden objects. It may happen that are formed agglomerates of pests that because of their size resonate with electromagnetic field. This opportunity can be studied with the model of scattering of the spheres. If the clusters of pests are approximated to spherical shapes, the

problem can be solved by the exact solution of the Maxwell equations. It was found that there are sizes of the sphere that cause the resonance, with a great power absorption with large temperature increase as showed in Figure 3.

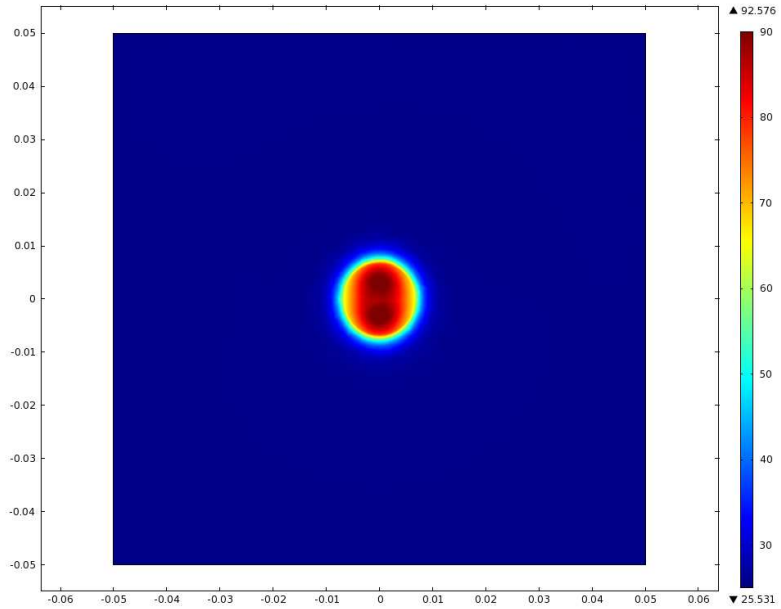

Figure 3. Temperature map in a transversal plane at resonance.

When the sphere's dimension is far from that of resonance, the wood around heats it. But when the sphere dimensions is near the resonance value, it's the wood which is heated by it raising its temperature to dangerous values, unpredictable with other methods. With simulation, though it is possible to find the exact solution as in the case of the spheres, was examined the behaviour of ellipsoidal objects, with similar results. Is therefore of primary importance, irradiating artworks, the evaluation of the possibility that resonances occur, in order to avoid irreparable damage to cultural heritage unique and unrepeatable.

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