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Improving Quality of Microwave Heating by Packaging – Analytical Approach

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Abstract. *The lecture considers the recently emerging ideas of developing non-metallic active packaging capable of improving uniformity of heating of food products processed by microwaves. Theoretical analysis supplemented by the advanced computer modeling shows that pursuing this goal by manipulating the materials traditional for passive packaging and enhancing their characteristics looks hopeless because of inability of those materials to properly influence the electromagnetic field. This conclusion is illustrated by the results of 3D computer simulations of SAR patterns within the food samples situated in the thin-wall paper box in a typical microwave oven.*

It is suggested that the technique of design of efficient focusing materials could be developed through the analysis of the problem of control and optimization of the electric field. Methods of optimal material design can be used to characterize configuration (microgeometry) and permittivity of the supplementary dielectric feelings guaranteeing appropriate redistribution of the electric field (and therefore the heat release) within the food products. Illustrative examples of the controlling materials for a rectangular waveguide conveyor applicator are presented. Class of materials suitable for such a control as well as the conditions required for transformation of the analytical approach into the applied practical technology are discussed.

Keywords. Computer Simulation, Field Distribution, Heating Uniformity, Microwave Heating, Optimal Materials Design, Paper-Based Packages, Packaging Materials, SAR Patterns.

Introduction

Packaging of food products subjected to the microwave thermal processing has been in the center of attention of engineers for many years. In contrast to *passive packaging*, which does not noticeably affect the microwave heating, the so-called *active packaging* has been known as the one that changes the electric field configuration and thus the heating patterns of the product contained within (Buffler, 1993). The first type of packaging is typically associated with *dielectric* microwave-transparent materials whereas the second one uses *metallic* elements reflecting the electric field either onto, or off the product (Bohrer and Brown, 2001).

There are many techniques of active packaging; virtually all of them have been developed due to sophisticated engineering intuition and extensive experimentation; the attempts to solve the uneven microwave heating problem by the field modification have been reviewed by McCormick (1991) and Bohrer and Brown (2001). Recently, some practitioners have become intrigued by the idea of whether it would be possible to produce packages (made from some specific dielectric materials), which could appropriately redistribute the electric field and thus generate uniform heat patterns *within the product*. The present paper responds to this interest and uses analytical means to show that this idea does not appear to be reasonable: it seems the required materials do not exist, or at least are currently unknown to the microwave engineers.

Problem of Control of Microwave Heating

Theoretical Background

There are many means aimed to even up the pattern of heat release. Despite evident attractive features of methods working on "statistical" principles (roundtables, stirrers, multiple input of energy, etc.), the practical implementation of these tools revealed the lack of uniformity in a number of important cases. These methods do not provide any control adapted to a specific material and an oven, and they are based on a purely intuitive expectation that the diversity of participating modes will secure the uniformity of heat release in space-time.

There also are attempts to improve the temperature patterns generated by a single mode, such as formation of the TEM mode, supplementary metal ridges and grids, the mechanical change of the chamber's size, and the use of evanescent modes. All these efforts implemented the so-called "deterministic" principles, which appear to be insufficient because the geometry of material included as well as their deployment throughout the operating chamber is motivated by engineering experience alone, both theoretical and experimental. In spite of its obvious merits, this experience is limited, and it therefore fails to completely exhaust the possibilities of improvement intrinsic for the system itself.

In order to release these additional hidden resources, a rigorous mathematical consideration is necessary. The effective way to put the temperature distribution under direct control has been suggested by Lurie and Yakovlev (1999, 2000). The required formalization emerges from the idea of optimal material design (OMD) (Lurie, 1993). In the context of microwave thermal processing, it means an optimal placing of supplementary dielectric materials within a part of the operating chamber in order to appropriately focus the electromagnetic field onto the heated product to maintain the desired (e.g., uniform) heat release within. The location, structure, and permittivity of a focusing material are determined by the OMD method. They are found not empirically, but rigorously as the means guaranteeing the required heat release.

This approach allows us to make an assessment of the major characteristics of possible packaging materials, i.e., estimate the preferable range of the complex permittivity and the most reasonable configuration.

Illustration of the Field Control – Rectangular Waveguide

Non-Absorbing Material

Real packages in which microwavable food is packed are typically characterized by quite whimsical 3D configurations. However, for the required estimate, it is sufficient to determine the actual trend by considering a simple model 2D-problem, for example, like the one shown in Fig. 1. If the material in *P* is supposed to be lossless (non-absorbing), the uniformity of the electric field (E_y) is controlled. The aim is to locate controlling materials in the lateral domains ($F_{1,2}$) to obtain a uniform field distribution of the electric field inside *P*. The question is: what will be the layout and the permittivities of these materials to guarantee the required uniformity?

The answer to this question can be obtained with the use of the OMD-based approach suggested by Lurie and Yakovlev (1999). The uniform field E_y within *P* is maintained if

(a) the effective permittivities ε_{F1}, ε_{F2} of controlling layers are uniform in each of the *F* domains, and

(b) the values of ε_{F1}, ε_{F2} exceed ε^*, and the permittivity increments $\Delta\varepsilon_{F1} = \varepsilon_{F1} - \varepsilon^*$, $\Delta\varepsilon_{F2} = \varepsilon_{F2} - \varepsilon^*$ depend on the operating frequency *f* and location of the processed material according to the formula $\Delta\varepsilon_{F1,2} = \left(\frac{h}{\omega}\right)^2$, where $\omega = 2\pi f$, and $h = \begin{cases} \dfrac{\pi}{2x_1}, & \text{for domain } F_1, \\ \dfrac{\pi}{2(a - x_2)}, & \text{for domain } F_2. \end{cases}$.

Fig. 2 illustrates the effect of the controlling material in the standard WR940 waveguide at 915 MHz. The highly non-uniform profile of the electric field within the processed material (Fig 2, b) is almost perfectly corrected (i.e., made uniform) when the controlling material is applied in both lateral domains *F* (Fig. 2(c)). Its dielectric constant (DC) $\varepsilon' = 6.71$ was determined with the use of the presented formula for the permittivity increment.

If there is an air gap between the processed and controlling material, the latter is also capable of making a similar effect. In this case, the parameter *h* determining the permittivity increment is calculated as a root of a certain transcendental equation.

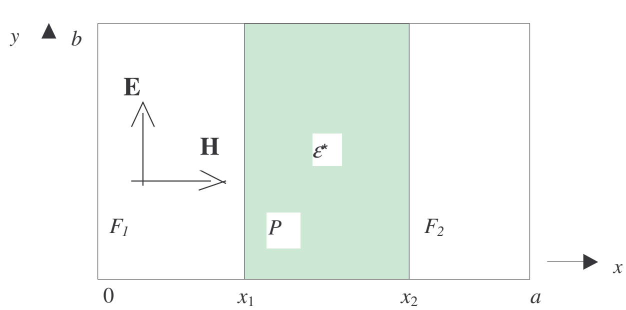
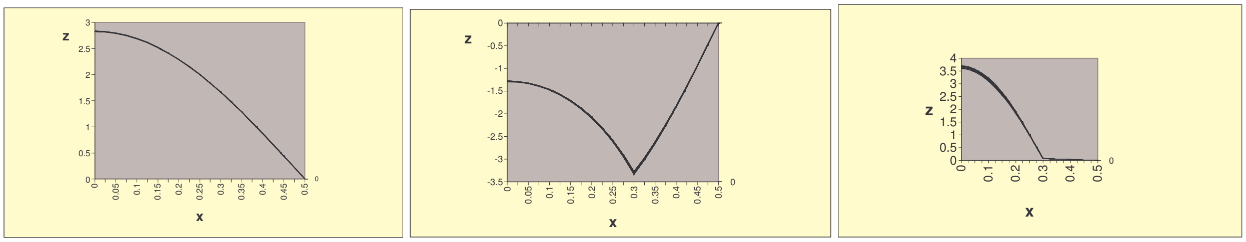


Fig. 1. Cross-section of a waveguide applicator with the dominant (TE_{10}) mode: *P* is the domain with the processed material, $F_{1,2}$ are the lateral domains for placing the controlling materials.



(a) (b) (c)

Figure 2. The vertical component of the electric field of the TE_{10} mode in a symmetrical half of an empty rectangular waveguide (a), in presence of a centered dielectric layer (the DC $\varepsilon^* = 5.5$, the interface at $x = 0.3$) (b), and the layer and controlling material ($\varepsilon_{F1,2} = 6.71$, $0 < x < 0.3$) (c).

The major feature of the both cases is: the DC of the controlling material is always larger than the one of the processed material. If the thickness of *P* is large, the permittivity increment becomes significant. If *P* and *F* are not in direct contact, then the larger the gap, the larger the permittivity increment. Similarly to the no gap case, the larger the thickness of the processed material, the larger the permittivity increment is required to make the field within *P* uniform.

Absorbing Materials

The case of domain *P* occupied by lossy (absorbing) material is characterized by a crucial feature. As shown by Lurie and Yakovlev (2000), the uniformity of the field within the processed material necessarily demands that the controlling material should also be assumed lossy, at least, provided that this material is uniform. There emerge two options:

1. to allow for the lossy controlling materials and thus secure the field uniformity in the processed material;
2. to admit certain *non-uniformity* of the field within the processed material by preserving the controlling material lossless and at the same time non-uniform.

The first option appears to be impractical because it would mean heating of the controlling materials. So it is reasonable to agree on some non-uniformity of the field within the processed material by preserving the controlling material lossless (or, possessing negligible losses). The non-uniformity of the controlling material then becomes a decisive factor that will affect the degree of non-uniformity of the field within the processed material. The microgeometry of the structure in *F* can be found in the framework of a special procedure. Whatever one gets as the microgeometry, the DC of each component in the layout is expected to be larger than ε^*.

Controlling Materials

The DC of the typical microwavable food products is known to be very high: the real part of complex permittivity is usually between 30 and 70 (Buffler, 1993). At the same time, as followed from the above consideration, the DC of the efficient controlling materials is expected to be larger than the one of the food. If the thickness of the controlling material is supposed to be small, this requires further increasing of its DC. In other words, it appears that the required materials should possess $\mathrm{Re}(\varepsilon_F)$ about 40-150 and $\mathrm{Im}(\varepsilon_F)$ about 0.0005-0.005.

Obviously, there exist no traditional (paper-based) packaging materials characterized by such a permittivity. Therefore, the efficient control of the field (and the heat release) by such packages appears to be impossible in principle. The only materials, which may have the required values of the complex permittivity, can be found in certain groups of ceramics. The cost of these ceramic materials is very high, and technologically “ceramic packaging” is unfeasible.

Food Sample in a Paper Box – Results of Computer Simulation

The heating patterns of the food sample in a thin-wall package placed in a microwave oven are illustrated below by a direct computer simulation. The computation was performed with the use of *QuickWave-3D*, ver. 2.0, a commercially available universal 3D electromagnetic solver implementing the conformal FDTD method. The scenario was designed for the *Daewoo* 800 W 0.9-liter domestic oven (internal size: 320 x 330 x 214 mm). For temperature $t = 5^oC$, the processed cylindrical material (diameter 50 mm, height 74 mm) at the frequency $f = 2.45$ GHz has complex permittivity $\varepsilon = 10.6 - i3.5$, conductivity $\sigma = 0.47$ S/m, and density $\delta = 0.48$ g/cm^3.

The sample was supposed to be put into a rectangular paper box containing two equivalent bottom and top parts with 1 mm gap between them; common length is 120 mm, width – 60 mm, height – 80 mm; thickness of the walls is 1 mm. If $t = 5^oC$, at $f = 2.45$ GHz its complex permittivity is $\varepsilon = 2.6 - i0.9$, conductivity $\sigma = 0.122$ S/m, and density $\delta = 1.2$ g/cm^3. The box containing the food sample was centered on the bottom of the oven (Fig. 3).

QuickWave-3D has proven to be effective for problems of microwave heating (Yakovlev, 2001) particularly because of a number of its specific options especially suitable for solving problems of microwave thermal processing. Computation was performed with the non-uniform mesh of cubic cells of 5 mm size in air, 3 mm cells in the material, 1 mm cells in the paper walls; the total number of the cells in the model was about 454 thousand.

Table 1 demonstrates the heat release within the considered materials (the packaging rectangular box and the cylindrical food sample). It includes the SAR patterns in the six horizontal layers with the thickness of 6.4 mm. It is seen that the chosen product will be heated extremely non-uniformly. Each cross-section possesses a significant “hot spot” flowing between the center and the left surface of the cylinder facing the open end of the exciting waveguide. The maximum of dissipated energy in these “hot spots” varies with the height and appears to be largest at the level about 17 mm from the bottom (about ¼ of the height of the sample).

The only cross-section with relatively uniform energy distribution (the top of the cylinder, the max/min ratio in the pattern is about 3.5) is associated with the smallest value of the dissipated power. At this height, more energy is released in the packaging box than in the sample product.

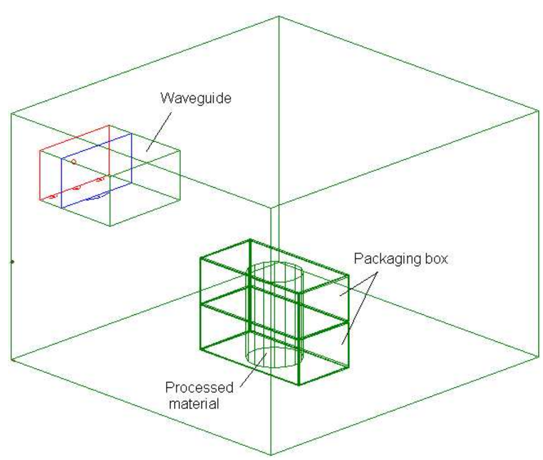
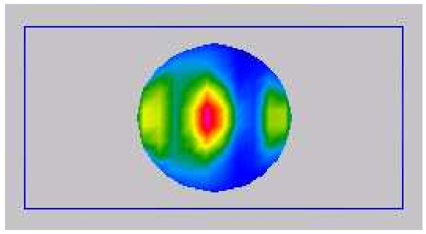
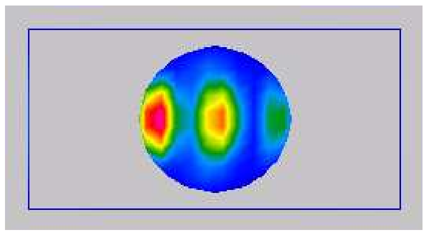
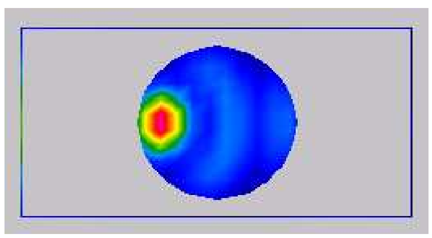
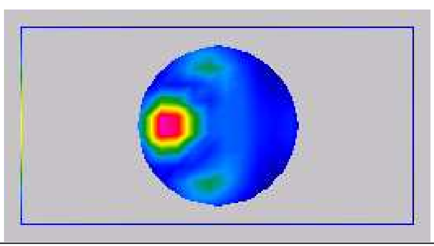
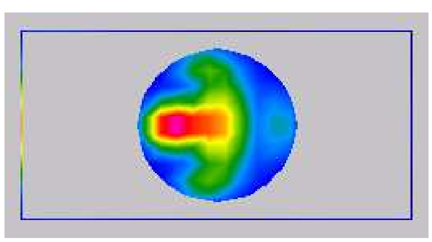
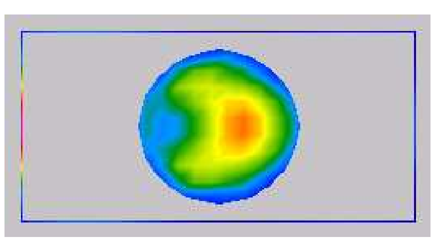


Fig. 3. 3D view of the model in *QuickWave-3D*’s Editor with conventional configurations of the box and the food product.

Table 1. SAR Patterns in the Food Sample in the Box

Horizontal Layer	SAR Pattern	SAR values, W/kg
z =0 ÷ 6.4 mm		*Product*: 13.1 (max) *Box*: 1.6 (left wall, center) 1.5 (right wall, center) 0.2 (top wall, center) 0.3 (bottom wall, center)
z =13.9 ÷ 18.5 mm		*Product*: 25.6 (max) *Box*: 4.7 (left wall, center) 1.1 (right wall, center) 0.3 (top wall, center) 0.3 (bottom wall, center)
z = 27.8 ÷ 32.4 mm		*Product*: 16.0 (max) *Box*: 8.6 (left wall, center) 0.3 (right wall, center) 0.1 (top wall, center) 0.1 (bottom wall, center)
z = 41.7 ÷ 46.3 mm		*Product*: 10.2 (max) *Box*: 7.0 (left wall, center) 0.5 (right wall, center) 0.1 (top wall, center) 0.1 (bottom wall, center)
z = 55.5 ÷ 60.1 mm		*Product*: 8.1 (max) *Box*: 6.2 (left wall, center) 0.7 (right wall, center) 0.1 (top wall, center) 0.2 (bottom wall, center)
z = 69.4 ÷ 74.0 mm		*Product*: 3.6 (max) *Box*: 4.4 (left wall, center) 1.0 (right wall, center) 0.1 (top wall, center) 0.1 (bottom wall, center)

Moreover, it turns out that the bottom wall of the package is strongly overheated. In the “hot spot” located near the sample’s surface facing the waveguide the absolute maximum of microwave energy is released, and its value is larger than the maximal energy released in the processed material. This happens in spite of the fact that the sample product is characterized by larger values of complex permittivity than the box material and the thickness of the package wall is only 1 mm. The bottom wall of the box appears to have the strongest gradient in the heat release (about 1,000).

The vertical walls parallel to the direction of the waveguide propagation encounter insignificant heating. The central parts of the walls perpendicular to the direction of the waveguide propagation are overheated with the ratios about 100 and 30 for the wall in front of the waveguide and for the opposite one respectively. The maximum values of energy released in these box walls are comparable with the maximal values of energy in the “hot spots” of many cross-sections of the sample product.

Computational experiment conducted for the same cavity and the load in the absence of the package box shows practically no difference in the SAR patterns of the food sample.

This example shows that packages made from a typical paper-based material can sustain overheating even if the thickness of the walls is very small. However, such a package is unable to change the heat pattern of the processed product contained within. This observation resulting from the computer simulation appears to be consistent with the reasoning derived from the analytical approach estimating characteristics of the efficient controlling materials.

Conclusion

The presented analysis based on the idea of OMD has shown that experimenting with materials typical for the packaging technologies is unlikely to lead to any meaningful results practice-wise. The paper-based and other traditional materials are not characterized by the required values of the dielectric constant (40-150) to influence the field within the food.

It has been, however, demonstrated that appropriate redistribution of the electric field (and therefore the heat release) can be achieved by the use of supplementary materials with high permittivities placed in the same cavity. In general, these materials appear to be composite. The microgeometry and DC of the components can be found with the aid of OMD techniques.

Currently, the capabilities of this approach are limited to the problems of control and optimization of the electric field in 2D structures with the finite number of modes. Appropriate theoretical development of the concept of OMD for 3D “deterministic” structures as well as the expansion of the technique over the dissipated energy rather than the electric field should open an avenue for substantial progress in solving the key problem of the microwave heating – obtaining the desirable (in most cases, uniform) heat release. Finally, the suggested technique could lead to the creation of new efficient applied technology of control over microwave heating.

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