UNDERSTANDING MICROWAVE HEATING IN CAVITIES IN USE TODAY

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Abstract

The presentation deals with developments and state-of-the-art in microwave heating applicators in the last decade. There is unfortunately a lack of information to academia from industry, both by the difficulties in assessing what patents are valuable and further the state-of-the-art, and by the increasing gap between scientific papers on microwave modelling and the actual use of commercially available, highly versatile modelling software. Some glimpses of a more complete picture of what has and can be done are presented orally and in a poster session.

Introduction

My decision to make this presentation stems from a long keynote presentation about understanding microwave heating cavities, held by Dr. Howard Reader at the AMPERE conference in 2001. He had also recently published a book [11] in the matter. I was at first astonished that he did not address some of the major developments in microwave oven technology in the last 10 years or so. I made the conclusion that he had not succeeded in getting information from those in industry who develop modern systems. It seemed that he had not found clues in the patent literature either. However, that literature is often difficult to use in research, since the primary reason is protection and not education.

Due to the very large scope of the presentation, only some few basics and examples are presented in the following areas:

- Some properties and limitations of the "well-stirred" multimode cavity – and an experimental method to evaluate cavity characteristics.
- Other phenomena in the cavity: load edge overheating and other modes: Brewster, quarterwave and evanescent resonant modes, trapped surface (LSM) modes
- The problems of resonant frequency variability in single mode cavities and applicators; a solution being counteracting load and cavity resonances.
- Large single mode cavities
- The increasingly "floating" differences between cavities and open-ended applicators.

The "Well-Stirred" Multimode Cavity

The concept is that with as many cavity volume modes as possible in the cavity, the heating patterns of these will overlap – by small frequency changes of the magnetron, by the permittivity changes of the load, or by adding a metal propeller (stirrer) in the cavity ceiling which will cause a time-sharing intensity variation of the relative strengths of the available modes. Hence, cavity design is directed towards finding cavity dimensions and excitation means which would support as many volume modes as possible – without really considering if there are any "better" or "worse" modes in terms of load interaction and heating evenness. This is a serious flaw, as is the fact that there are several other kinds of modes than those possible in an empty cavity.

The theory was first described in the literature in the end of the 60's [1; 2], and considered only simple TE and TM volume modes in the empty cavity. Neither hybrid modes[1] nor some important zero order modes[2] were dealt with and it can be said that these early works have lead much of the subsequent development astray. Unfortunately, some contemporary literature [11] is also quite incomplete and has not improved the situation. There is not yet any sufficiently useful published theory for how cavities with several simultaneous modes actually work, in spite of there being more than 250 million microwave ovens in use in the world today. This perhaps astonishing fact has several reasons, some of which are:

- The theory is complex and generalisations as well as simple optimisation procedures are not possible by pure mathematical (analytical) methods. Hence, multimode theory is not a good subject for academic research.
- The influences on the heating result by the load itself are clearly significant in many cases. This has led to the conclusion in industry that the load variability as such is the major performance-limiting factor. Hence, industry interest has also in general diminished and microwave oven design is

1 The simple kind of hybrid mode referred to here is characterised by the lacking E or H field component (of the six; maximally five exist) being in another direction than that of the main power flow; in this presentation that is considered to be the vertical direction.

2 This is a mode with no field variations along the vertical direction.

done in many companies by just copying older, reasonably well-functioning cavities and feeds.

Cavity Mode Analysis by the Electromagnetic Ray Concept

A useful approach is to use a so-called electromagnetic ray concept or waveguide mode theory of electromagnetic fields [3]. It then becomes possible to introduce an equivalent angle of incidence θ towards the cavity floor area for each possible mode, of a set of four symmetric rays also having a specified polarisation. This angle can be generalised by its sine being >1, to correspond to evanescent modes ($\sin\theta = f_c/f$ where f_c is the mode "cut-off" frequency). This sine also corresponds to the usual so-called separation constant $(\lambda_0/\sqrt{2}) \cdot \sqrt{(m/a)^2 + (n/b)^2}$, where m; n are the horizontal mode indices and a, b the corresponding cavity dimensions in the x (width=left-right) and y (depth) directions. One can then calculate (by analytical functions) the envelope of (i.e. maximum possible) absorbed power in a load covering the whole cavity cross section in a cavity at constant frequency but with θ as variable (i.e. for all possible horizontal cavity dimensions). Of course, one has then to introduce several normalisations when bringing in the cavity data: a=b=1; m=n=1; λ_0=1; omission of some constant factors; the reflection factor refers to the H field for TM modes. – Such a result is shown in Figure 1. – It is seen that there are "normal" cavity volume resonances with vertical indices p = 3, 2 and 1. However, the largest available power is under quarterwave resonant ("beyond Brewster") conditions (p=½), for which the mode impedance is higher in the load than in the cavity space above. The non-resonant Brewster mode condition is characterised by its vertical wavelength $\lambda_{B,g}$ in the cavity space being $\lambda_0 \cdot \sqrt{|\varepsilon_B + 1|}$, where the load permittivity ε fulfills the geometric optics Brewster condition $\sqrt{\varepsilon} = \tan\theta$. – It can be shown by experiments as well as numerical modelling that the quarterwave resonant and Brewster

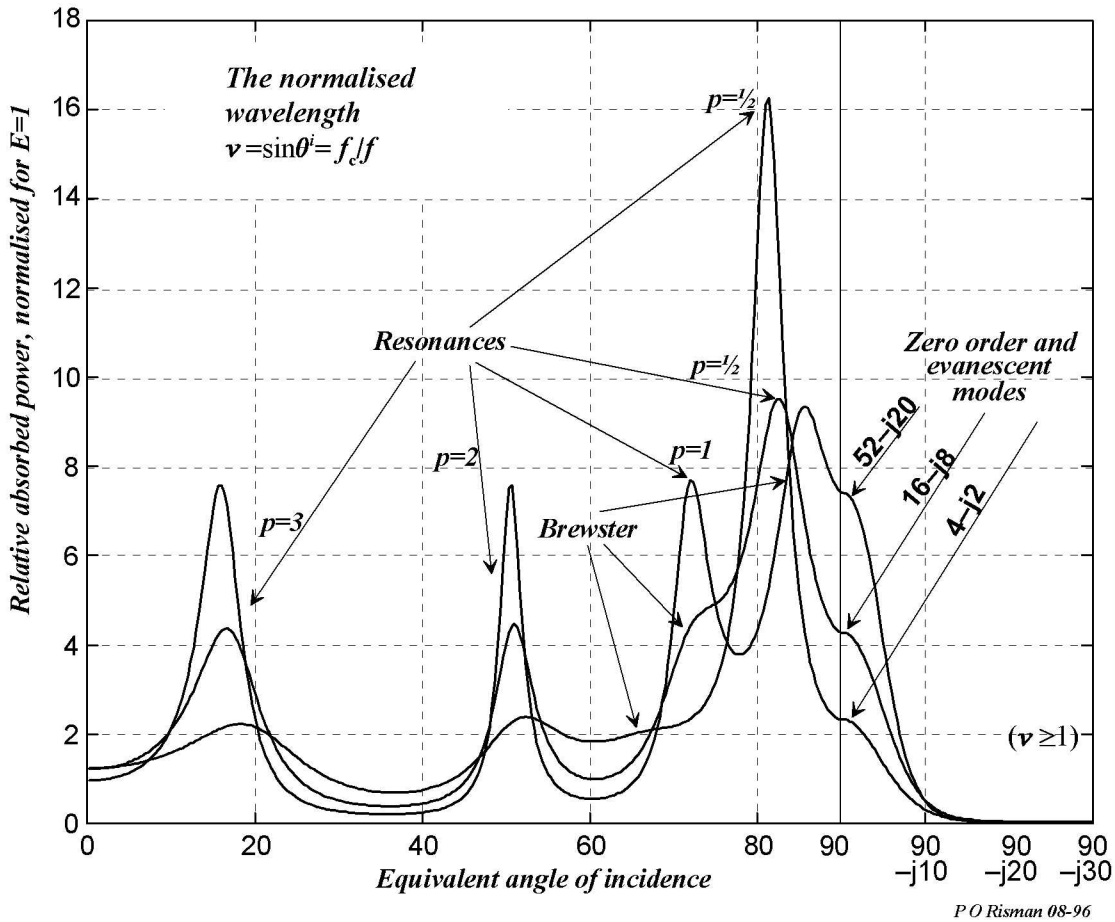

Figure 1. Envelope of TM power absorption in 190 mm high 2450 MHz top-fed cavities with a thick dielectric load at the bottom

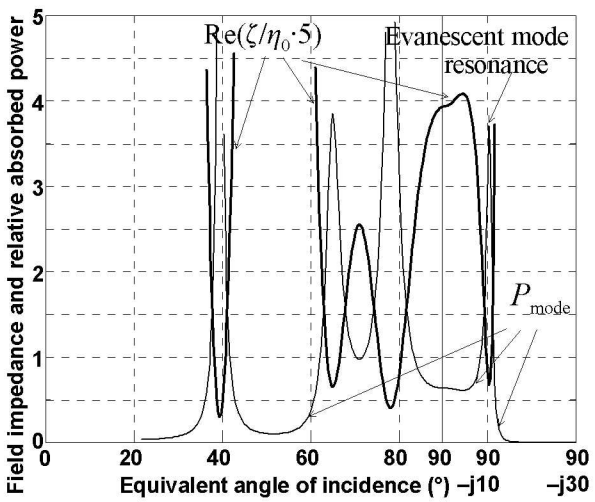

Figure 2. Field impedance (real) and relative possible power absorption in a 3 mm thick load with permittivity 52–j20; 160 mm airspace above and 20 mm below.

mode conditions actually persist also when only about 15 % of the cavity cross section is covered.

A further class of cavity volume modes is evanescent resonant. Their existence was briefly reported as a curiosity in 1989 [5], but they are actually used in some industrial systems for heating of thin loads. An evanescent TM type cavity mode is capacitive, and dielectric loads are inductive, so a compensation effect may occur. A typical equivalent incidence angle in such cavities and applicators is (90–j8)°, corresponding to a cavity energy decay distance of about 70 mm at 2,45 GHz. – An example is shown in Figure 2, where the field impedance[1] ζ is also given. Not only does this figure show the existence of such modes, but also the intriguing fact that mode field impedances are about the same at resonance, which can be used to explain the fact that different modes "take over" the power when loads change, by an "automatic" amplitude compensation effect.

Cavity Mode Analysis— the Double Layer Method

For the general case of a multimode oven one may say that there are so many different active modes in time sequence or with variable degeneracy that the load in it can be considered to be equally irradiated from all directions and with all polarisations. In real cavities, however, certain equivalent directions and polarisations normally dominate. This allows quantification of the seriousness of edge overheating of loads sensitive to that phenomenon (see below), and it also becomes possible to use certain test loads to "measure"

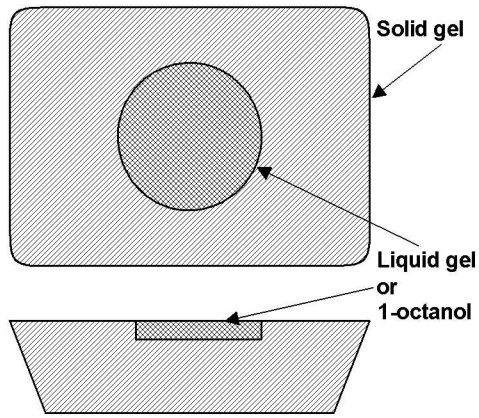

Figure 3. The test load.

these directional characteristics and polarisations. – Briefly, the procedure is based on comparative differences of absorption in two double layer slab-shaped loads having very different (in a first case) and the same (in a second case) real permittivity of the thin top layer. The load is shown in Figure 3 and consists of a cast solid gel [4] (ε=52–j20) slightly larger than a single portion ready meal and with a central depression about 70 mm diameter and 5 mm high. Liquid gel substance and 1-octanol (ε=3,1–j0,30) are used in the two comparative runs, since they give about the same heating rate. They are poured into the depression, which is covered by clingfilm.

It may be shown that a "perfect" multimode cavity gives $\theta \approx 45°$. Further details are given in the poster, as are details on the experimental techniques to obtain a high accuracy.

Results for five microwave ovens are shown in Table 1 (next page), with descriptions of general oven characteristics. The results are largely self-explanatory, and the poorer performance in the last case may be due to deterioration of the favourable modes caused by metal reflections of the strong longitudinal-section magnetic (LSM) modes under the load.

Modern Microwave Ovens

In 1992, Whirlpool in Europe presented a microwave oven having only two dominating cavity volume modes, one of these being a Brewster mode. This mode type is enforced by using a two-port resonant waveguide which maintains a certain phase difference between the ports [6]. The excitations and field types also have other important advantages: strong underheating modes and reduced edge overheating (see below).

1 This is the vectorial sum of the impedances of the transmitted and reflected mode, at the fictitious ceiling plane of excitation.

Oven #	Heating rate quotient ε=3/52	θ^i (°) (appr.)	Oven characteristics
1	0,82	49	Industrial 0,9 m³, 2,4 kW batch oven
2	0,82	49	Large cavity US "power shower" household oven with large stirrer
3	0,99	63	Simple Japanese turntable household oven
4	1,05	69	Well-performing commercial oven
5	1,12	78	Dual resonant side feed household oven[1]
5 modif.	0,93	57	Same as #5, but with metal plate below the load
1 Described later; Whirlpool oven.			

Table 1. Measured/calculated θ^i in some microwave ovens

A consequence of the developments over the last ten years is that today perhaps about half of the household oven models offered to the world market are not multimode in the conventional meaning. Other examples are some models by Matsushita/ Panasonic and De'Longhi, and as shown in the previous section, an experimental method can be used for characterisation of their mode properties. Actually, in many ovens there are only two specific modes in action for all loads down to about 200 cm³, and one of these is replaced by a third mode with small loads such as when popping popcorn. This is in spite of the fact that the cavities are more than 300×300×200 mm large, so that such a cavity could actually be designed to support about five modes. However, controlled magnetron frequency jumping (a so-called long-line effect phenomenon) is also used in some oven models.

The Edge Overheating Effect

This is a non-resonant diffraction phenomenon caused by the E field component parallel to the edge (the TM-polarised case, now with the edge as reference direction) of in particular high permittivity loads. It is indeed remarkable that this important phenomenon in microwave heating has not received the attention it deserves, in comparison with cavity mode theory. A possible reason may be that analytical methods cannot be used to derive descriptive equations. However, an equation for the internal E field in the edge tip can actually be derived by an approach using a wave potential term and a diffraction term based on Fermat's principle and an idea by Young (1802), except for a diffraction source amplitude constant. By experiments and modelling this constant has been found to be 1 (with insignificant error), so the complete equation becomes

$$\frac{E}{E^i} = \frac{2}{1+\sqrt{\varepsilon}} + \frac{1\cdot(90-\alpha)}{180+\arcsin(1/\sqrt{\varepsilon})} \qquad (1)$$

where E is the field inside the wedge tip, E^i the incident field, ε the load permittivity and 2α the sector angle. – There is no such effect for TE-polarised case (E^i perpendicular to the edge) and the edge tip is then actually heated less than the surrounding load parts – see the comparative TM and TE polarised cases in Figure 4; the energy flow is from "below". The corresponding equation in the TE case is the same as in the electrostatic case, so the heating intensity at the edge becomes very small. The edge overheating effect for TM polarisation is much stronger – in many cases the tip region is heated more than six times stronger than adjacent flat parts – than by the "explanation" often given in the literature: as a simple addition effect of irradiation from two directions.

Under-Heating (LSM) Modes

A particular class of modes may exist between the cavity bottom and the underside of the load, in "good" microwave ovens, and are characterised as trapped surface waves (LSM waves) lacking the vertical H field component. The theory for such modes (which are not cavity volume modes) has been applied to microwave ovens [7], but the important aspects on how to properly excite these modes and possibly make them resonant was not addressed, for

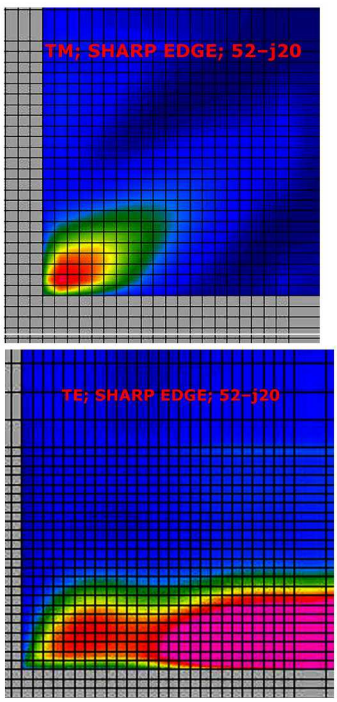

Figure 4. Modelling of wedge heating in the TM case (above) and TE case; ε=52–j20. 2,45 GHz;1 mm raster. Wave entering from below.

competitive secrecy reasons. What is needed are strong inwards-going cavity bottom currents at the turntable edge, a very low impedance of the associated horizontally directed TE type wave and a proper "receiving function" by the electric thickness and position of the turntable and its distance to the cavity bottom. The common statement in the literature that the load should normally be $\frac{1}{4}\lambda_0$ from the cavity bottom for best results is thus just coincidental, at best.

Amplification by partial LSM mode resonance may be achieved with a recessed cavity bottom. The excitation criterion is typically fulfilled by a dominating Brewster-like cavity volume mode having a y index 1 (and consequently a high x index such as 5[1]).

It is generally desirable to have a significant under-heating capability in microwave ovens and such ovens using the dual resonant feed [6] or other enhancing systems such as a phase quadrature Brewster and resonant quarterwave mode combination [8] typically have more than 40 % of the total load power by the under-heating modes. This allows efficient use of so-called crisp plates: metal containers with a ferrite rubber flat glued to the underside. Such ovens became a great success for Whirlpool in the 90's, and helped to bring the company to #1 market position in Europe and #3 in the world at the end of the decade. – A modelling example showing also LSM modes is shown in Figure 6.

Reduction of Resonant Frequency Variability in Single Mode Cavities

Multimode cavities have the drawbacks of the edge overheating not being controlled or reduced, and the loose coupling to the load resulting in various types of load external and internal resonant phenomena, as well as circumferential standing surface wave phenomena – all contributing to poor prediction and control of the heating evenness in load types prone to such phenomena, such as high permittivity loads with flat surfaces. However, as has been addressed earlier, the use of Brewster and quarterwave resonant modes result in less variability of the coupling to different loads, and since such modes are non-resonant they offer a means of improvement. It can be said that the tolerance requirements are moved from the load to the cavity.

In single mode resonant cavities for smaller loads, many of the multimode problems can sometimes be eliminated, but the system resonant frequency dependence on the load geometry and permittivity may still persist.

Constant resonant frequency may be accomplished using a partially resonant load which is circularly cylindrical, in an essentially circularly cylindrical cavity resulting in the system TM_{120} mode [9]. The method works well within a high-permittivity load diameter range of about 20 to 35 mm at 2450 MHz, for pumpable foods.

A similar self-regulating effect may also occur with very small hollow applicators of high-permittivity ceramic, intended for heating of small elongated loads such as liquids in tubes or vials. However, such design work would be too tedious and costly were it not for the important tool of numerical microwave modelling, using a commercially available software [10].

Large Single Mode Cavities

It is generally believed that the size of single mode cavities needs to be comparable to or smaller than the free space wavelength. That is indeed not the case, and two different examples will be shown [in the podium presentation]: drying of wood by high-order arch surface TE modes in long tanks having a diameter up

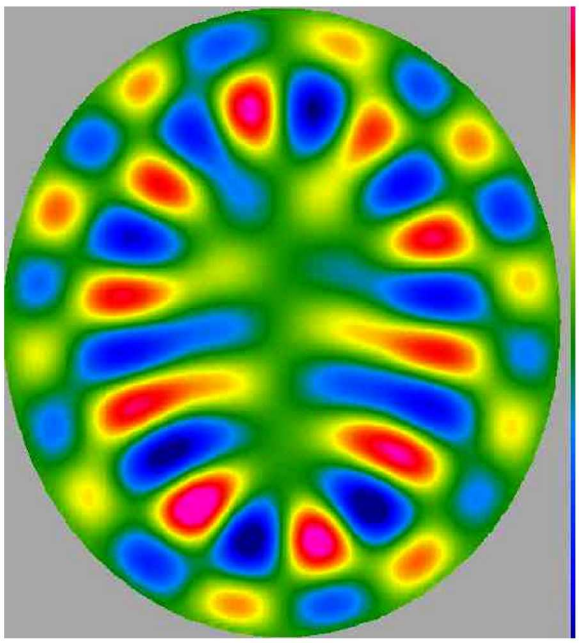

Figure 5. The vertical E standing wave pattern of the $TM_{10;2;1}$ mode in the ceiling of a loaded elliptical cavity with about 770×670 mm cross section.

1 Interestingly, this Brewster mode (which is actually a hybrid TEy_{51B} mode in most cases) is rather common in "good" household microwave ovens. This is evidenced by cavity widths of the oven population having a strong concentration around 325 mm (the depth is not so sensitive due to the index 1 in that direction).

to $10\times\lambda_0$, and drying of fruit and similar in large single high-order circular or elliptical TM arch surface mode cavities at 2450 MHz with about 100 or 200 mm height. – An example of the mode pattern in the latter cavity is in Figure 5, where it is seen that the fieldless centre region is reduced by the cavity ellipticity. – Again, numerical modelling results in drastic savings of design time and cost.

Are some Open-ended Applicators Cavities?

This example deals with multiple downwards open-ended applicators used in industrial tunnel ovens for drying of products such as food components and wood, or pasteurisation of food products. When designed for 2,45 GHz multiple magnetrons, crosscoupling may be a problem, as will of course tunnel end leakage, as for all continuously operating equipment. Of course, even heating is a primary concern, in particular with loads in which the heating is not partially self-regulating as in some drying operations.

Figure 6 shows a modelling result for a system with 105 mm high applicators, energised with the TEy_{31e}[1] mode. The applicator mode is resonant, by its capacitive excess energy being balanced by the mode mismatch to the "free space" below, and a propagating non-resonant TEy_{11} helper mode in the applicator which also balances off the horizontal H field at the inter-applicator wall openings and contributes to the concentration of the vertical energy flow.

It is seen (by the waveguide fields) that the cross-coupling between applicators is very low (it is <–20 dB) and that the LSM mode at and below the loads is partially controlled by the bottom plate metal serrations. In addition, the very small a/m factor for this mode strongly reduces coupling and leakage along the tunnel. This is about 620 mm wide, and each applicator triplet is sideways offset by about $\frac{1}{4}$ wavelength, to obtain an even heating.

Conclusions

This brief overview of some of the state-of-the-art microwave heating cavity principles indicates that microwave heating system developments are progressing and that some of these have indeed influenced the microwave oven market in the last 10 to 15 years. However, very little of this development is made within or in connection with academia – but instead in secretive companies and by some few self-employed individuals. There is a lack of communication between academia on one side and industry and these individuals on the other. It seems as academia should include more of the patent literature in their searches for news, but what inventions may become successful – and to what extent patents tell a sufficiently complete story – are other difficult matters to assess. Less secrecy and an improved exchange of information are needed for creating a better general understanding, for providing good literature to the new generation of engineers and researchers in microwave power – and for stimulating industry to develop designs based on today's and not yesterday's state-of-the-art.

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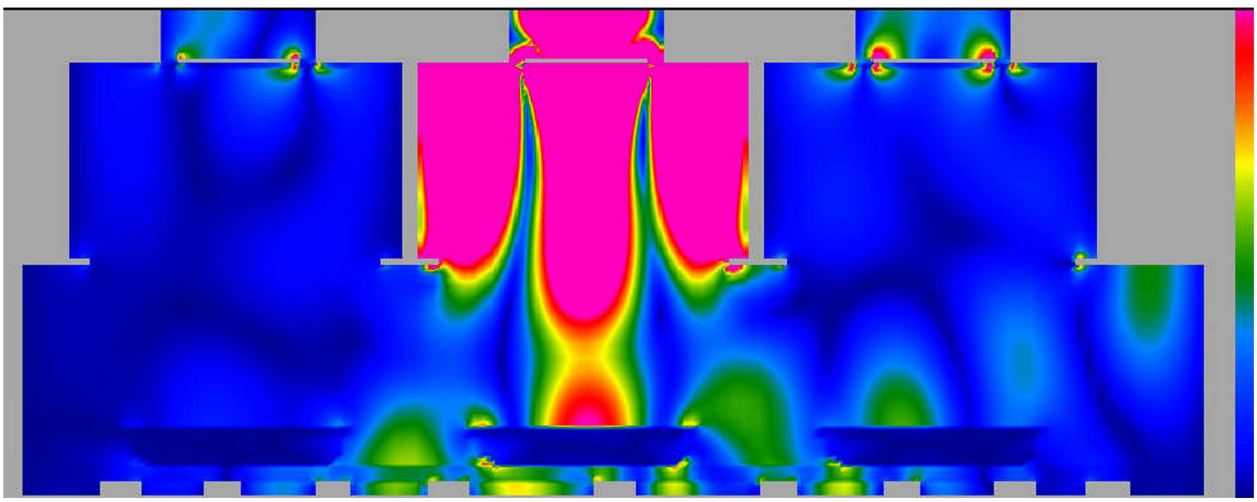

Figure 6. Envelope of the vertical E field in an evanescent mode rectangular 3-applicator set with only the centre applicator energised, above a 120 mm high tunnel with single portion food loads.

1 The letter e stands for evanescence, i.e the normalised vertical wavelength v of the mode is >1. (See Figure 1)

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