1D and 2D Coupled Electromagnetic-Thermal Models for Combined Convective-Microwave Heating in a Pulsing Regime

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Introduction

For over 40 years, the microwave power industry has been interested in optimizing the uniformity and efficiency of microwave heating, a process which is known to be, by its nature, internal and inhomogeneous. While the problem of efficiency has been recently clarified and some modeling-based optimization procedures minimizing reflections from the cavities have been proposed and found viable, the challenge of non-uniformity of temperature fields still remains unresolved. Moreover, it appears that it has not been received a clear conceptualization and formalization yet.

A fundamental idea of microwave heating process *with variable characteristics* can be put in the background of the related discussion. Traditional stirrers, round-tables, conveyor lines are well known existing implementations of this approach. In applications in which the load size is not negligible in comparison with the wavelength, *static* microwave processing inevitably leads to overheating of particular zones and the formation of stable *hot* and *cold spots*. This suggests that only certain *changes* in the key characteristics of the heating process, e.g., in the electric field structure (aimed by the stirrers), in the patterns of dissipated power within the load (addressed by the motion of the load on the conveyor belt), etc. may change the resulting heating pattern. One thus can conclude that a series of motivated and controllable variations of process characteristics can be considered a mechanism capable of eventually evening up the temperature pattern.

One approach which may be taken in dealing with variable characteristics is pulsing of microwave power, in which periods of thermal relaxation between periods of heating are allowed. Since the rate of microwave heating is higher than the rate of heat relaxation, one cannot expect that the temperature field would become even due to the heat diffusion while microwave power is on, but this would be obviously possible when it is off. While the idea of pulsing microwave energy has been around for a while and tested in some R&D projects, no definite conclusion on the search for an appropriate balance of heating and relaxation periods has been generated. Characteristics of a pulsing regime have never been computationally studied.

Another (much more popular) technique exercised in engineering practice to directly affect a heating pattern has been the use of combined convective and microwave heating. There is experimental evidence of the efficiency of this option in scenarios in which conventional heating is applied on the load surfaces while inner areas are heated by the microwaves. The produced effect is also caused by heat diffusion as the means of reaching the underheated zones and making the heating pattern more even. However, a real potential of this combination in efficient influencing the resulting temperature field remains insufficiently clear.

Quantitative characterization of heat diffusion occurring at the surface (convection heating) and internally (pulsing) appears therefore to be of significant interest since it may clarify the role

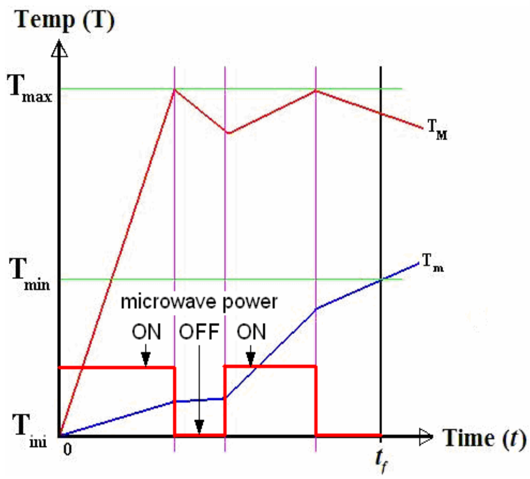

Fig. 1. Conventional interpretation of microwave pulsing

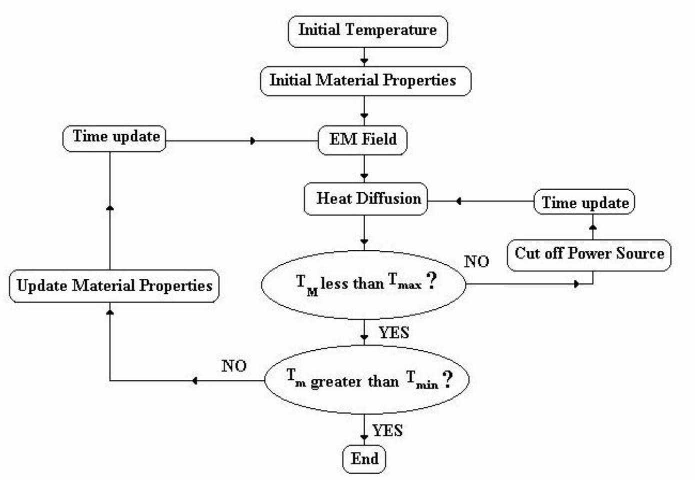

Fig. 2. Flow chart of the algorithm implementing the solutions of the coupled problem in a pulsing regime.

which thermal relaxation may play in making heating patterns uniform. In this paper we present the original 1D and 2D models for computation of temperature fields generated by combined convection-microwave heating in a pulsing regime. These models implement the solutions of the two-way coupled electromagnetic-thermal problem with temperature-dependent electromagnetic and thermal parameters (namely, dielectric constant ε', the loss factor ε'', heat conductivity K, heat capacity c, and density ρ). While these models are not applicable to practical (essentially 3-dimensional) microwave heating systems, they still us to analyze general trends in influencing the resulting temperature fields by the pulsing microwave energy and by the combined convective-microwave heating in scenarios with certain idealizations.

Pulsing and Its Implementation

Functionality of pulsing microwave energy in making the temperature pattern more uniform is illustrated in Fig. 1. The curves T_m and T_M represent the lowest and highest temperatures over all points in the load respectively as functions of time. The difference between T_M and T_m can be interpreted as a measure of heating non-uniformity. The values $T_{\min}$ and $T_{\max}$ represent the minimum and maximum temperatures, respectively, between which the temperature of the (relatively uniformly) heated load is required to be. When T_M reaches $T_{\max}$, the microwave power source is turned off, and thermal diffusion occurs in the load. The trend during these periods of thermal diffusion is, naturally, that the minimum temperature increases, and the maximum temperature goes down toward the average temperature. When T_M has relaxed sufficiently, the microwave power source is turned back on. This process is repeated until T_m reaches $T_{\min}$. The related computational scheme which we suggest for simulation of the described pulsing mode is presented in Fig. 2.

The related 1D analytical-numerical solution is implemented as a *MATLAB* code. The 2D model is built in the finite-element-based *COMSOL Multiphysics* ver. 3.2. The 1D and 2D problems analyzed with these models are the derivatives of the 3D structure consisting of a 100 mm section of WR975 (248 x 124 mm) waveguide and a layer of lossy material (thickness of 30 mm) on the shorting wall (Fig. 3). The operating frequency is 915 MHz, so the applicator is excited by the TE_{10} mode (i.e., by the mode with the only component of the electric field E_z).

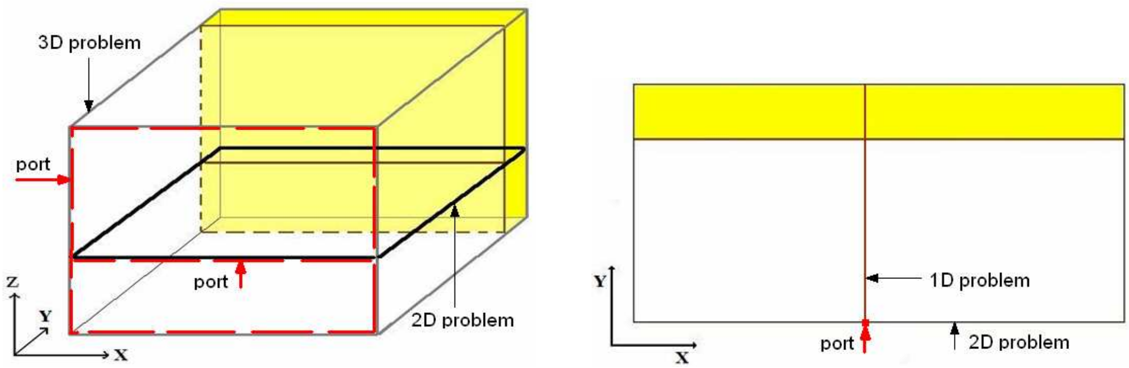

Fig. 3. Geometries of the original 3D- and the derived 2D- and 1D scenarios.

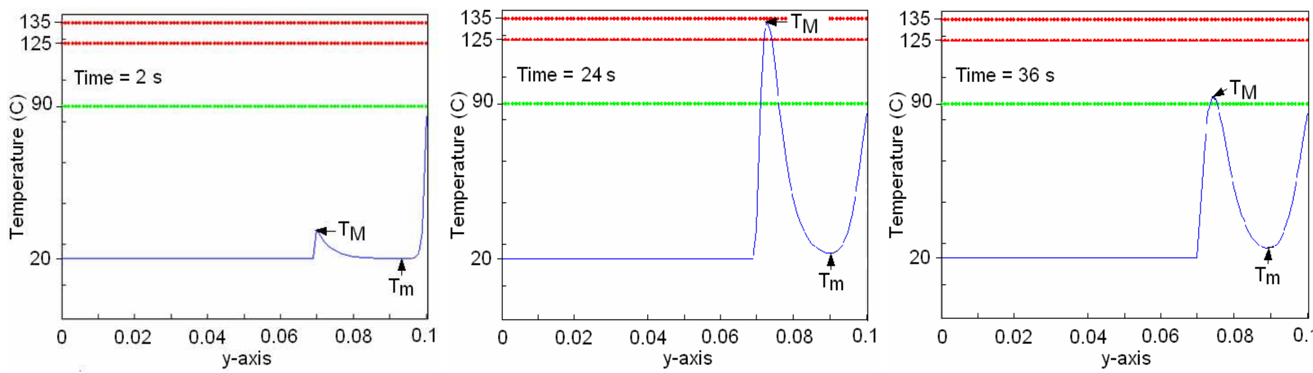

Fig. 4. 1D problem: maximum and minimum temperatures due to the microwave pulsing (1/0 kW) and external heating; temperature on the cavity walls is 90°C. After 2 s: T_M = 34.0°C, T_m = 20.0°C; after 24 s: T_M = 134.3°C, T_m = 22.5°C; after 36 s: T_M = 97.4°C, T_m = 24.5°C.

The material parameters of the load are taken in accordance with the data for raw beef at 915 MHz as $\varepsilon'(T) = -0.00445T + 3.4548$, $\varepsilon''(T) = -0.09897T + 77.34635$, ρ = 1,060 $J/(\text{kg}^0K)$, c = 2,210 kg/m^3, and K = 0.69 $W/(m^0K)$. An external heat source is imitated by appropriate boundary conditions constituting a fixed elevated temperature – at a point (1D model) or on a contour representing the waveguide walls in contact with the load (2D model).

For validation purposes, the temperature values obtained for the described scenario by the 1D and 2D models were compared to each other and found to be fairly close. Furthermore, a series of temperature patterns obtained after different heating times by the *COMSOL* model were compared with the ones computed with the 3D modeling software *QuickWave-3D*. The closeness of the temperature patterns and final maximum and minimum temperatures confirm that, for the present scenario, our models provide reasonably accurate representations of the microwave heating that occurs in three dimensions.

Results and Discussion

The 1D computational experiment presented in Fig. 4 shows the distribution of temperature generated by a microwave pulse and convective heating from the waveguide wall. Microwave power is kept on until maximum temperature reaches the upper constraint $T_{\max}$. The power is

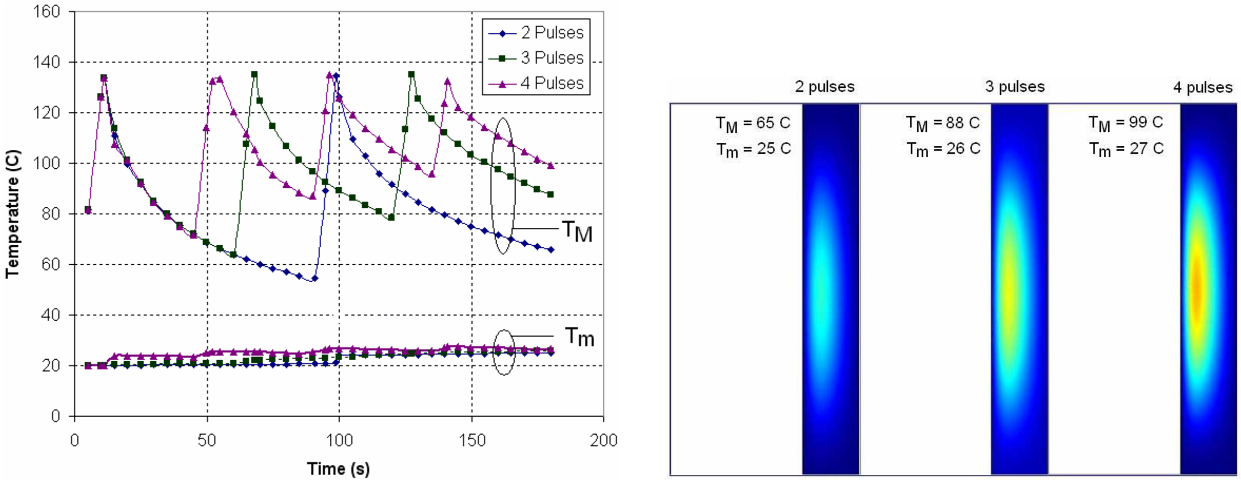

Fig. 5. 2D-scenario: maximum and minimum temperatures due to the microwave pulsing (1/0 kW) alone.

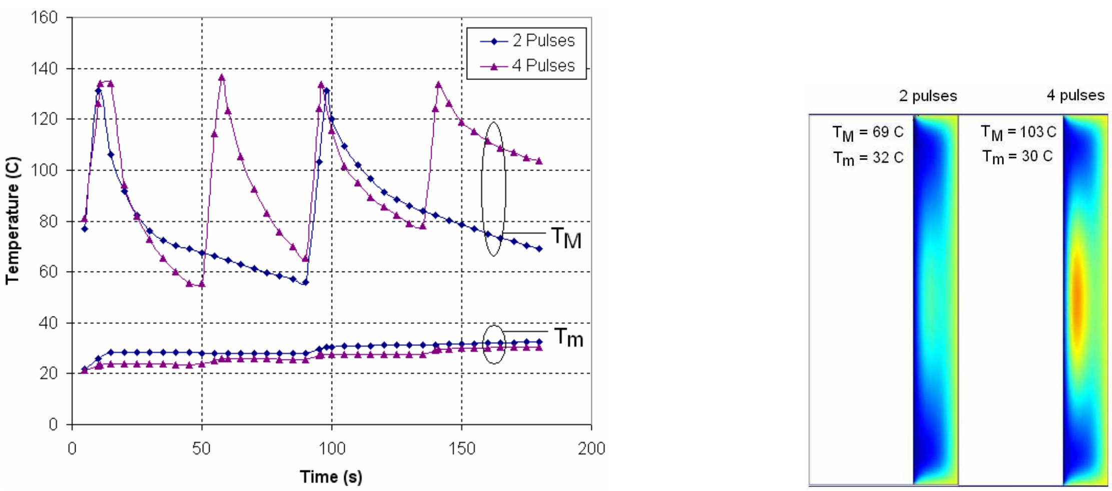

Fig. 6. 2D-scenario: maximum and minimum temperatures due to the microwave pulsing (1/0 kW) and external heating; temperature on the cavity walls is 90^{o}C.

then turned off, and T_M decreases and T_m increases. The latter goes up due to thermal diffusion from both the microwave-generated hot spot and the external source.

In the 2D computational experiments described below, we subdivide the 3-minute total time interval into a number of heating cycles $N = 2, 3, 4$ (same as the number of pulses), and for each cycle, we heat the load up to the chosen maximum temperature ($T_{\max}$ = 135^{o}C), then allow thermal relaxation until the end of the cycle. The results obtained for different numbers of pulses in the absence of conventional heating from the surface are shown in Fig. 5. As N increases, we observe a significant rise in the T_M, but very little increase in T_m. The steady, gradual nature of the rise in T_m reveals that there exist internal zones which are virtually unaffected by the microwave heating; regardless of variations in the applied power, these zones experience increase in T_m only due to thermal diffusion.

Computational results obtained in the presence of convective heating from the surface are shown in Fig. 6. The combined heating notably changes the temperature pattern – the load's area adjacent to the cavity's walls (the source of heat) is characterized by a raised temperature. The values of T_m in the end of heating time are a little bit higher due to the fact that the external heat source affects the load also during thermal relaxation and provides additional heat to the medium. Nevertheless, a large zone within the load (close neither to the hot spot, nor to the heated surface) remains cold – it will only ever be heated by thermal diffusion.

Our general observations from a series of 1D and 2D computational experiments are:

- Microwaves heat only particular areas within the load. Other areas are heated only due to thermal diffusion; either an external heat source, or time, or both are needed to target these areas; the time could be significant.
- During fixed heating time, increases in a number of pulses results in significant increases to T_M, but limited increases to T_m.
- With a fixed number of pulses, increased heating time leads to greater thermal uniformity, and lower T_M and T_m.
- There is a direct proportionality of uniformity of temperature fields to the time allowed for thermal diffusion.

Conclusion

We have developed, for the first time, 1D and 2D two-way coupled models simulating microwave and combined microwave-convective heating by a pulsing electromagnetic energy. While it appears to be impractical to extend the 2D *COMSOL* finite element model to a 3D version (because the latter would enormously increase the required memory resources even in case of very simple small-size scenarios), the way we couple the electromagnetic and thermal problems in *COMSOL* allows us to relatively simply implement a pulsing regime and conveniently study its general trends in affecting the resulting temperature fields in the load. With this model we can clarify the capabilities of the pulsing technique before its implementation in a 3D FDTD algorithm.

From the computational results generated by these models we tend to conclude that pulsing, along with other techniques of changing key characteristics of the heating process (e.g., supplementary external heat source, alterations to geometry, variation in excitation, etc.), is an important option in achieving uniformity in temperature fields. Since our models can accommodate different geometries, boundary conditions, and material properties, they can be very suitable instruments for the related computational experiments.