Coupled Electromagnetic-thermal 1-D Model of Combined Microwave-convective Heating with Pulsing Microwave Energy

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Abstract— As a result of the well-known tendency of microwave (MW) heating to develop hot and cold spots in practically unpredictable locations, special measures must be undertaken to simultaneously bound the maximum temperature (which occurs at the hot spots) while still sufficiently heating the rest of the object (in particular, the cold spots). This difficulty has been ameliorated with use of turntables [1], or mode stirrers [2], or multiple feeds [3], while an alternative approach used in industry, which has not been systematically studied yet, features a MW pulsing regime [4] in which periods of relaxation allow the effects of thermal diffusion, a naturally-occurring mechanism that operates on a vastly different time scale from MW heating, to make the temperature distribution more uniform.

This contribution presents an algorithm and modeling software allowing for 1D simulation of thermal processing of dielectrics by pulsed MW energy. The presented technique is a continuation of our earlier study [5], which first presented software to consider the pulsing regime as a technique to ensure heat diffusion through the load in the time intervals when the microwave is off, and thus to evaluate its efficacy as a controlling parameter in making the resulting temperature field more uniform. The algorithm is also capable, in accordance with industrial practices, of simulating combined MW-convective heating. Here we report an upgraded version of the algorithm and a new series of computational experiments which allow us to see the pulsing regime with different pulsing parameters on the materials with different electromagnetic and thermal properties and with the new option of adiabatic boundary conditions.

The software is implemented as a MATLAB code executing an analytical-numerical solution of a 1-D fully coupled electromagnetic-thermal problem, with temperature-dependent electromagnetic parameters (dielectric constant and the loss factor) and thermal parameters (heat conductivity, heat capacity, and density). We account for these dependencies in the solution of the coupled problem using a special numerical procedure implementing a finite-difference computational scheme. Similarly to [5], performance of the code was validated by the 3-D conformal FDTD simulator *QuickWave-3D* [6].

While a 1D solver cannot be applied to realistic MW heating systems and be considered as a tool for practical CAD, it is effective in the context of studying the functionality of a MW pulsing regime, and as it is fully parameterized, can be used to study pulsing in the context of a variety of scenarios actually used by industry.

A series of performed computational experiments shows that microwave pulsing in combination with convective heating at a temperature equal to or greater than the minimum temperature required for the load to be sufficiently heated is more effective than microwave pulsing alone, because during periods when the microwave is off, diffusion is conditioned by both thermal conductivity and additional heat introduced to the load. Naturally, when the boundaries are maintained at a temperature lower than the intended minimum threshold, then truly sufficient heating can never be achieved; yet, even this kind of convective heating is beneficial for uniformity in the first stages of heating. We also note the general trend that the greater the number of pulses over a given time interval, the more quickly uniformity is achieved. The developed model can therefore be conceptually and specifically instructive in designing practical applicators with pulsing MW energy.

REFERENCES

1. Kopyt, P. and M. Celuch, "FDTD modeling and experimental verification of electromagnetic power dissipated in domestic microwave oven," *J. Telecomm. & Information Techn.*, No. 1, 59–65, 2003.
2. Plaza-Gonzalez, P., J. Monzó-Cabrera, J. M. Catalá-Civera, and D. Sánchez-Hernández, "Effect of mode-stirrer configurations on dielectric heating performance in multimode microwave applicators," *IEEE Trans. Microwave Theory Tech.*, Vol. 53, No. 5, 1699–1706, 2005.

3. Pitarch, J., A. J. Canós, F. L. Peñaranda-Foix, J. M. Catalá-Civera, and J. V. Balbastre, "Synthesis of uniform electric field distributions in microwave multimode applicators by multifeed techniques," *Proc. 9th Conf. Microwave & High-frequency Heating*, 221–224, Loughborough, U.K., 2003.
4. Gunasekaran, S. and H.-W. Yang, "Effect of experimental parameters on temperature distribution during continuous and pulsed microwave heating," *J. Food Engineering*, Vol. 78, 1452–1456, 2007.
5. Feldman, D. A., E. M. Kiley, S. L. Weekes, and V. V. Yakovlev, "Modeling of temperature fields in 1D and 2D heating scenarios with pulsing microwave energy," *Proc. 41st Microwave Power Symp.*, 130–134, Vancouver, BC, Canada, 2007.
6. *QuickWave-3D*, QWED Sp. z o.o., Warsaw, Poland, 1998–2009. http//: www.qwed.com.pl/.