SIMULATION OF MICROWAVE HEATING USING FINITE ELEMENTS

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Introduction

Microwave heating is used extensively in industry for processing many materials ranging from foodstuffs to ceramics and from rubber to wood, in systems from a few to many hundreds of kW's. Typical applications include tempering of meat, fish and fruit, pasteurising of bread, drying of snack foods, curing of rubber or manufacturing of high grade lumber products. Many different varieties of applicators exist, ranging from horn-like radiators to serpentine structures and from single mode cavities for treating well defined geometrical loads such as filamentary or planar materials to multimode ovens for processing large irregular objects [1].

The design of these systems has, to a large extent, been empirical except in the very few cases where an analytical solution is available. This is very expensive because it entails building costly prototype equipment for testing with the materials under investigation. More recently, however, computational modelling has started to make a significant contribution in the design of such systems by being able to predict the electric field distribution and subsequently the temperature inside the heated material. In such a way many changes can be made without having to build expensive prototypes. We report on one such numerical scheme that has been devised in our laboratory to analyse problems in microwave heating as well as in other areas of electrotechnology [2].

The numerical scheme

A computer programme has been written in C++, based on a finite element formulation which can be run either in the frequency or time domain depending upon the particular problem under consideration[3]. In the time domain the system is excited using a Gaussian pulse followed by a FFT or DFT to obtain solutions at different frequencies. The advantages of the time domain are that it involves simple or no matrix inversion, it gives rise to well conditioned matrices, it allows non-sinusoidal excitation which in turn affords multiple frequency solutions. The downside is that the frequency resolution is poorer than its frequency domain counterpart and many time steps are required. The frequency domain, on the other hand, is much faster for small problems, has good frequency resolution but suffers from the disadvantage of requiring solution of a large system of equations and the solution is only at a single frequency. Although there are other methods that have been developed to tackle problems on microwave heating, such as finite differences, method of lines, TLM and so on[2], we have chosen finite elements because of its versatility and its distinct advantage, say, over the more common finite difference technique, in that it overcomes the problem of "staircasing" when a geometrically irregular object is being considered. The system that we have developed can use nodal as well as edge elements, however, the latter are preferred because they suppress spurious modes, they handle interfaces more naturally and they accurately represent the fields at sharp corners[4].

The solution process involves three stages. Pre-processing, where the system is meshed using a commercial mesh generator (FAM) and where the material properties are assigned, the solution stage, where the equations are formulated and solved using iterative or direct techniques and a post-

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processing stage where the quantities are derived and the results displayed. Having obtained the electromagnetic field solution by solving Maxwell equations, the power density can be computed and inserted into a heat flow equation, with feedback if necessary, to compute the ensuing temperature inside the material being processed. The code thus far is not able to handle phase changes such as those encountered in unit operations.

Examples in microwave heating

(a) High loss materials

The code described above has been applied to numerous cases of microwave heating in resonant and non-resonant systems. One of the first examples to be considered was that of heating a small tray of mashed potato (of relative permittivity, as measured using a co-axial probe and a network analyser as, 65-j20), measuring 210x 90x30 mm placed symmetrically in a multimode microwave oven of internal dimensions, 391x292x300 mm dimensions and excited by a waveguide, WG9A, connected symmetrically in a side wall. The time domain method produced a solution in under four hours on a Sun Sparc-20 workstation when the field was time stepped for 100 cycles at 2.45 GHz using 30 time steps per cycle. By comparison the frequency domain required about 67,000 iterations of an incomplete Cholesky pre-conditioned QMR algorithm to reduce the residual to below $5x10^{-7}$, producing a solution in 43 hours. Validation of the numerical solution was obtained by measuring the surface temperature using an infrared camera. Mashed potato has a low thermal conductivity so that the surface temperature provides a good indication of power density distribution.

Progressing to more realistic situations in the case of food processing three further cases where examined. First, a food-like material such as batter (38.3-j9.2) which is made up of equal amounts of water and flour was prepared, and used to fill a Pyrex dish of 135 mm in diameter to a depth of 30 mm. This dish was then placed asymmetrically on the long centreline of the cavity 20 mm from the side and 50 mm from the bottom and rested on a block of low loss polystyrene. This system was meshed using FAM which generated 275,746 elements and 326,184 unknowns (edges). The simulation was run for 50 cycles and solution took about ten hours. Once again validation was obtained by comparison with the data from a thermal camera image of the top of the sample after it was heated for one minute with an injected power of 500 W.

Secondly, a Bird's Eye Menumaster™ turkey platter was then modelled. This consisted of two slices of turkey (40-j14), three potatoes (60-j20) which were assumed to be spherical, 4 carrots (80-j17) and a sausage (35-j12) all placed on a plastic tray which was not modelled. Again FAM was used to produce a tetrahedral mesh, this time consisting of 173,071 elements which produced 208,024 unknowns. The model was run for 40 cycles at 2.45 GHz which took about 8 hours. Finally, a tray of 4 mince pies consisting of a pasty case (3-j0.5) partially filled with mince meat (13.5-j7.5) was also simulated. This time the mesh consisted of 188,042 elements and was again time stepped for 40 cycles of the field taking 17 hours.

(b) Low loss materials

A plastic block was chosen as typical low loss material to be treated in the multimode microwave applicator described above. The dielectric properties were now represented by 2.5-j0.01 and the block, placed symmetrically in the oven, measured 200x200x25 mm while the mesh for this problem contained 64,887 edges giving 56,064 unknowns. Solution in the time domain gave rise to the computed power density distributions which were very sensitive to frequency, in the range 2.44 to 2.475 GHz. A thermal image plot of the power density indicated that the nearest match to the computed power densities was at 2.46 GHz a result which was confirmed by measuring the magnetron spectrum which showed its output to peak at 2.455 GHz. Such a result points to the necessity of being able to compute the electric field and power density over a range of frequencies around the operating frequency of the source in a system which treats a low loss dielectric. This is because the applicator loaded with a low loss material represents a high Q-factor situation and as such the different modes do not necessarily overlap in space and giving rise to the observed effect.

Other areas of electroheat

Radio frequencies, typically at 13.56 or 27 12 MHz, are used extensively in industry for heating materials such as paper, textile, polymers and for welding plastics[2]. The finite element code has been used to compute the electric field, and the ensuing power density, in a lossy dielectric placed in typical industrial applicators, such as a through-field for example, where the electric field established is perpendicular to the planar electrodes. Either the Laplace or the wave equations are solved to obtain the electric field distribution depending upon the frequency of operation, the type and properties of the material being processed and its physical size[5]. For systems of the order of a few metres and for frequencies exceeding about 50 MHz it is necessary to solve the wave equation. Standing wave patterns are observed in the applicator. Validation is obtained by measuring the impedance using a network analyser and comparing it with the value computed through the numerical scheme[6].

Parallel processing

Solution times for problems involving domestic size microwave ovens, even without feedback, run to many hours. For a continuous industrial processor which may handle many hundreds of kg per hour solution times using a workstation may be well above 100 hours, assuming that the workstation had sufficient RAM to solve the problem at all. This is unacceptable and parallel processing, using a cluster of multi-processor workstations or a supercomputer will speed up processing times considerably. We will report on our current efforts to write software in order to use the domain decomposition technique to solve large industrial systems for microwave heating. Use will be made of the existing C++ finite element code and message passing between workstations will be implemented using the PVM model which has been built around the virtual machine concept.

Conclusions

A finite element programme was written capable of producing the electric field and temperature distribution in materials heated with microwave, as well as other forms of electrical energy. Formulation in the time as well as frequency domain using edge elements is possible. For very large industrial problems in electroheat it is essential to be able to run the code in a supercomputer thus reducing processing times quite considerably.

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