Numerical analysis of microwave heating: Fundamentals and applications

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Abstract. In recent years, microwave-assisted materials processing applications are on the rise in terms of novel processes being developed and increased coverage of materials that can be processed. In general, the studies have been of experimental nature. Since microwave heating has extensive application in food processing at an industrial scale, literature on the research involving numerical studies is available in this domain. It is primarily focussed on determination of the distribution of temperature and the rate of heating of a food sample. The evolution in materials processing applications using microwaves has paved the way for exploring numerical analysis to predict and control the response parameters required for efficient material processing. This paper presents the theoretical background of electromagnetic wave propagation along with the heat transfer mechanism required in the numerical studies of microwave heating. The steps for this multiphysics-based numerical analysis are also discussed. An account of the state of microwave heating simulation research is presented as well. The unpredictability of microwave heating mechanisms coupled with fast-developing novel applications makes microwave heating simulation quite challenging. In addition, the merits of such numerical analysis present a case for extensive future research.

Symbols

\( E \) intensity of the electric field, \( Vm^{-1} \)
\( E_{rms} \) Root mean square (rms) value of Electric field intensity, \( Vm^{-1} \)
\( H \) Intensity of magnetic field, \( Am^{-1} \)
\( B \) Magnetic flux density, \( Wm^{-2} \)
\( D \) Electric flux density, \( Cm^{-2} \)
\( J \) Electric current density, \( Am^{-2} \)
\( \rho \) Volume charge density, \( Cm^{-3} \)
\( Q_{em} \) Power dissipated or Heat generated per unit volume, \( Wm^{-3} \)
\( \varepsilon \) Dielectric constant of the material, dimensionless
ε₀  Permittivity of free space, $8.852 \times 10^{-12}$ Fm$^{-1}$
ε''  Dielectric loss factor, dimensionless
ω  Angular frequency of radiations, rad s$^{-1}$
σ  Electrical conductivity, Sm$^{-1}$
ρ  Density, kg m$^{-3}$
C_p  Specific heat capacity at constant stress, J kg$^{-1}$K$^{-1}$
t  Heating time, s
T  Temperature, deg C
λ  Free space wavelength, cm

1. Introduction
Microwaves, an important constituent of electromagnetic (EM) spectrum has numerous engineering applications. Many such applications as based on its heating ability. Microwave heating has significant potential in the field of materials processing [1–4]. With the advent of technologies and processes to maximize the transformation of the energy possessed by electromagnetic radiation into thermal energy, extensive developments have taken place in materials processing applications involving thermal energy. These applications have demonstrated the merits of microwave heating over the conventional ways of heating the materials. These merits are quantified in the form of time and energy savings [5–7]. Still, industrial heating using microwaves is not carried out on a large scale partly due to limitations of versatility on the part of developed technologies and challenges owing to uncontrolled heating of materials which is a function of dielectric and magnetic properties. In addition, limited knowledge on mechanisms driving the rate of temperature rise in a material specimen also attributes to a lack of large scale commercialization. Numerical techniques such as finite element analysis can serve to enhance the predictability of the heating process and provide a platform for effective experimentation [8]. In the case of numerical analysis of microwave heating, a multiphysics approach is required that involves the coupling of the equations governing microwave propagation and the equations governing the conversion of microwave energy into heat and its transfer [9]. The subsequent sections present the fundamentals of wave propagation and methodology involved in numerical analysis. An overview of related studies is also presented.

1.1. Fundamentals of EM wave propagation
The microwave propagation is mathematically represented by Maxwell’s equations which are basically a description of physical laws [10]. These equations relate to the change of magnetic field and electric field with respect to space and time. The equations are as follows [11]:

\[ \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \]  \hspace{1cm} (1)

\[ \nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} \]  \hspace{1cm} (2)

\[ \nabla \cdot \mathbf{D} = \rho \]  \hspace{1cm} (3)

\[ \nabla \cdot \mathbf{B} = 0 \]  \hspace{1cm} (4)

From equations (1)-(4), it can be inferred that “electric field” and “magnetic field” are interdependent and time-varying. These fields in combination contribute in the subsequent generation of each other thereby leading to continuous wave propagation [10, 11]. For instance, the variation of the electric field in space as represented by equation (1) is a function of the variation in the magnetic field with respect
to time. The same is true for the generation of the magnetic fields, according to equation (2) with an addition of current density term. The presence of partial derivatives in the expressions also points toward the fact that these variations (in the electric and magnetic field) co-exist. These equations enable us to predict the intensity of the electromagnetic field inside the microwave cavity. Detailed discussion on these equations is available in the ref. [10].

1.2. Fundamentals of power dissipation and heat transfer
Microwave radiation’s heating ability is owing to the conversion of microwave energy into thermal energy. The rate of heat generated per unit volume due to microwave energy in dielectric materials is given by equation (5) and in conducting materials is given by equation (6) [12].

\[ Q_{em}(x, y, z, t) = \omega \varepsilon_0 \varepsilon'' E_{rms}^2 \]  
(5)

\[ Q_{em}(x, y, z, t) = \sigma E_{rms}^2 \]  
(6)

Thus, equations (5) and (6) express the loss in power per unit volume owing to the transformation of electromagnetic energy into thermal energy, in terms of root mean square (RMS) value of the electric field intensity in the local region with coordinates x, y, z and at time t.

The distribution of the temperature in the load (material being heated) is governed by the “heat transfer” equation based on the thermo-physical properties of the load being heated [13, 14]. Equation (7) expresses the rate of heat transfer.

\[ \rho C_p \frac{\partial T}{\partial t} = \nabla (k \nabla T) + Q_{em} \]  
(7)

The combined solution of equation (5), equation (6) and equation (7) along with the equations governing electromagnetic wave propagation yields temperature distribution and distribution of electromagnetic field in and across the material being processed. The analysis of these equations therefore results in multiphysics simulation.

2. General Steps of Simulation
A general flow-chart for numerical simulation of microwave heating is presented in figure 1. The first step is to create a model, either 2D or 3D that represents the actual physical geometry of the whole setup. It includes the oven cavity, material to be processed and the waveguide and the port and other components of the heating set-up. The use of 2D is generally preferred and applicable only in such cases where the load (material to be processed) is symmetric. However, the 3D model is the best alternative to ensure better accuracy of the desired solution. The subsequent steps are discussed in the following sections.

2.1. Material properties
The accuracy of the analysis depends significantly on the correctness of the material property values given as an input to the general-purpose programs such as COMSOL, QUICKWAVE, HFSS, etc. or custom codes. The important properties required at the pre-processing stage are dielectric properties of the materials, thermal properties such as conductivity and heat capacity, electrical conductivity, and density. In the case of metal processing using microwaves, susceptors play a critical role to achieve the desired temperatures. In fact, until it was successfully demonstrated by Roy et al. [15] that metals can also be processed using microwaves by using microwave hybrid heating concept (MHH). In MHH, a material with superior interaction with microwaves which is quantified on the basis of its dielectric property which is dielectric loss factor to be specific is used. Once it gets heated volumetrically, it transfers the heat to the surrounding region. Few of these susceptor materials used in various microwave processing applications are silicon carbide (SiC), charcoal, graphite, pure alumina (Al₂O₃), zirconia, etc. [16].

The key challenge in pre-processing step is to accurately determine the required properties. Loharkar et al. [16] have also summarized the various methods used for characterizing the dielectric properties which are critical in numerical analysis. In addition, these properties are temperature-dependent and
therefore, the analysis gets quite non-linear, which can also have an effect on the accuracy of the temperature distribution and field distribution profiles represented by the solution.

Figure 1. General steps in microwave heating simulation.

2.2. Initial and boundary conditions
Microwave heating is a combination of initial value and boundary value problems. Typically, the oven walls and the waveguide are assigned the boundary condition of perfect metallic conductors which is expressed mathematically as follows (refer to equation (8)) [17]:

$$E_{tangential} = 0$$  \hspace{1cm} (8)

The frequency of microwave irradiation is fixed at 2450 MHz. The initial condition in heat transfer modeling is primarily the temperature of the load to be heated before it is subjected to microwave irradiation.

2.3. Meshing
Mesh size and quality has a significant impact on the accuracy of the final solution along with the time required for processing. It has been established that the mesh size in dielectric material has a relationship with the wavelength of radiation in the free space and dielectric constant of material (refer to equation (9)) [14]. It results in minimizing the computational time along with the error in the prediction of temperature at 2450 MHz.
\[ h_{es} = \frac{\lambda}{\sqrt{\varepsilon'}} \]  

(9)

The element quality, another important criterion used in COMSOL multiphysics commercial package varies from 0 to unity for faster and robust convergence. An acceptable value of minimum mesh quality is 0.1 \[17\]. In addition, memory usage can also be reduced by using half models instead of full models.

3. Recent applications of microwave heating simulation

Pioneering work in simulation of microwave heating was performed in the field of food engineering and technology. Several researchers have used the numerical simulation tools to predict the rate of temperature rise in the food sample under consideration, possible locations of hot spot creation and effect of cavity size and geometry. One of the most popular numerical techniques used in the analysis of microwave propagation is a finite-difference time-domain (FDTD) method \[18\]. Krishnamoorthy \[19\] developed a mathematical model based on the solutions obtained by combining the electromagnetics and heat transfer phenomenon using Quickwave (v 7.5) software. The combined equations were processed using the FDTD method. Optimization of simulation parameters such as mesh size, electric field strength, heating time step and frequency was carried out to predict the temperature. This numerical model was validated using experimental results. Yarahmadi et al. \[18\] also used FDTD for determining the distribution of the electromagnetic field and to determine temperature distribution based on this information. In continuation of his work, Pitchai \[20\] used the finite element method (FEM) to estimate surface temperature patterns on various food samples. FEM is another extensively used numerical technique that offers the ability to analyze irregular geometries and complex boundary conditions \[14\].

COMSOL multiphysics software package is based on the finite element method \[21\]. Quite a few of the numerical simulation-based studies have been carried out using this software owing to its ability to model and analyze problems involving multiple scientific principles. For instance, it has been used in the food technology domain to study the drying of food grains. ElGamal et al. \[21\] developed models to predict the moisture and temperature profile across the bed of rice grains. Similarly, Pitchai \[20\] obtained the solution for temperature distribution using a commercial package based on FEM. The slight discrepancy in the results of the experiment and simulation studies was observed owing to unaccounted phenomena such as chemical changes in the sample, mass transfer, evaporation, etc. during the pre-processing stage.

Due to the inherent benefits of numerical simulation and evolving research in materials engineering domain, several simulation studies have been reported in materials processing as well \[22–31\]. Few of these materials are coal \[22, 30\], biomass \[25\], iron powder \[29\], silicon carbide \[32\]. As discussed earlier, the properties of the specimen to be heated are of utmost importance and govern the accuracy of the solution.

A detailed parametric study to quantify the effect of microwave heating of biomass has been presented by Halim and Switchenbank \[25\]. These parameters were the height of the specimen from the cavity bed, waveguide position, properties of the specimen to be heated, etc. This study has laid down the basis of further investigation, especially the optimization of microwave-based heating applications which is still an open field for research. A similar study on microwave heating of asphalt mixture has been carried out by Wang et al. \[26\]. The properties of asphalt mixture were determined using laboratory tests and the samples were heated in a commercial microwave oven to validate the simulation results. The model was based on fairly linear characteristics and therefore, the authors had proposed the inclusion of non-linear effects to enhance the applicability of the model for extensive analysis.

Lovas et al. \[27\] determined the dielectric properties experimentally and modeled the microwave heating of minerals such as andesite and other minerals at a frequency of 2.216 GHz using COMSOL multiphysics. The model was used to predict the temperature distribution in the mineral samples under the effect of irradiation.
To summarize, quite a few microwave-assisted heating applications have been simulated using numerical techniques. Commercial software packages are available that are based on a multiphysics approach and enable parametric investigation of microwave heating in a quick time without being dependent on physical experimentation.

4. Conclusion
Numerical techniques such as the finite element method have made a major contribution to enhancing the rate of advancements in the field of scientific and engineering analysis. The advent of general-purpose analysis programs and fast computational media have fostered a reduction in research and development cycle times. The discussion on the steps of the simulation process and recent applications presents an overview of modeling and analysis of microwave heating. Since, the domain of microwave-assisted materials processing is relatively in its earlier stages of development as far as its commercialization is concerned. The use of numerical simulation would contribute immensely to this task.

It has also been inferred that the accuracy of these simulations would require a thorough characterization of the materials being processed. Consequently, the numerical simulations will aid in achieving enhanced control and process predictability, which is still a major challenge in microwave-assisted processing of materials.

5. References
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