# Computer-Aided Analysis and Optimization of Microwave Heating Systems

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The application of microwave energy for thermal treatment of different materials and substances is a rapidly growing trend of modern science and engineering. Deep penetration of microwaves in dielectric media improves uniformity and intensifies the heating process. The variety of microwave heating devices like kitchen ovens, industrial plants, laboratory setups, and medical applicators is considerably large.

Design and optimization of microwave heating devices is impossible without theoretical studies of the physical processes of electromagnetic waves interaction with lossy dielectric media. Mathematical modeling and experimental measurements are the main tools for investigation of such processes. The development of applied electromagnetics, including the theory of numerical modeling, computational software and hardware, has led to the appearance of different mathematical models for simulating electromagnetic and thermal fields in microwave heating systems. Aggregate state of irradiated sample, operating temperatures, possible chemical or biological reactions, peculiarities of particular technology realization and some other factors, influence on the formulation of such models. The most well-known among them is the coupled electromagnetic heat transfer problem, which takes into account the influence of temperature on the distribution of microwave power sources in an interaction domain.

Such mathematical models can be built using numerous commercial software. One of them is the package COMSOL[1] on the finite element method (FEM), which is widely used in computer-aided design (CAD) of many microwave devices. This multi-physics software is suitable for the solution of coupled problems, which makes it a useful tool in modeling of microwave heating processes.

Another approach using the finite time-domain method (FDTD) is employed by the QuickWave-3D[2] (QW3D) software. The features of this software, such as conformal mapping of rectangular meshes and a new method to extract the wave impedance and propagation constant directly from time domain simulations, allow saving computer resources. The geometrical model of microwave device can be expressed in symbolic variables employing the so-called User Defined Object language. This makes the optimization process very flexible and efficient. Combined application of both packages for simulation of one object can increase the efficiency and accuracy of the numerical modeling. Here we consider a few examples of such approach.

### *Purification of polluted soils*

Contamination of soils is a very widely spread problem in many countries. The in-situ method of microwave decontamination of soils is an attractive alternative to commonly employed ex-situ technologies because it prevents possible intoxication during excavation and is much cheaper.

A coaxial antenna with an operating frequency of 2.45 GHz. shown in Fig. 1a, is intended for a realization of such an in-situ remediation method[3]. Different contaminants like oils and other chemical substances are evaporated during microwave heating of the soil and can then be exhausted. The antenna design includes a waveguide-coaxial transition, a one-meter coaxial line with 20 slots that is short-circuited at its end. It is equipped with a metal cone to easily insert the antenna into the ground. A standard rectangular waveguide WR340 is utilized as a feeder.

Theoretical and experimental studies of the described air-filled antenna, carried out in

Karlsruhe University[3], have shown quite good coupling for dry soils. However, for moist soils an increased reflection factor was observed. Additional numerical simulations by means of FEM and FDTD techniques have helped to upgrade this device and decrease antenna return loss for moist soils[4] as well.

Preliminary theoretical investigations fulfilled by using a simplified 1D analytical models of stratified dielectric media have demonstrated that the best result is achieved when the slotted antenna is separated from the soil by a 5-mm thick Teflon coating (Figure 1b). Figure 2 illustrates the numerical simulation results for different levels of moisture content in microwave exposed soils. The return loss at 2.45 GHz does not exceed 0.25 for the highest moisture content.

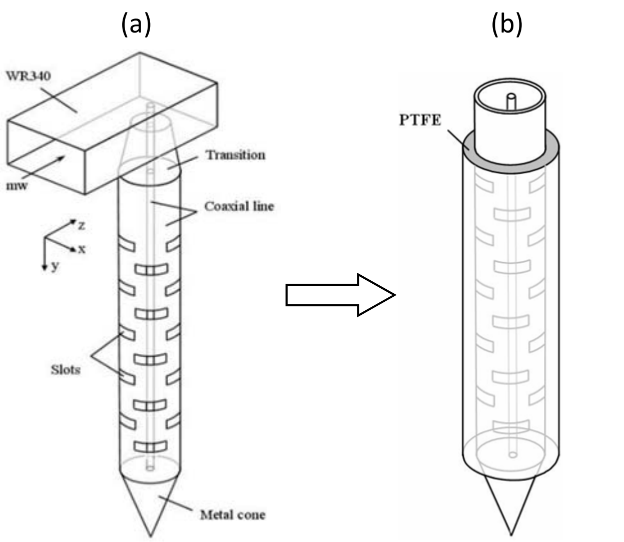


**Figure 1.** Initial (a) and upgraded (b) designs of the microwave antenna.

### *Chemistry reactors*

Electromagnetic (EM) energy has been proven to be a useful and helpful tool of scientific research nowadays. EM waves are widely used in experimental studies in physical chemistry, food science, medicine, biology, material science, and so on. It is known that microwaves accelerate many chemical reactions. Today microwave chemistry is one of the most rapidly developing trends of science and engineering. Early studies in this field employed conventional domestic microwave ovens. The special equipment required in analytical chemistry resulted in commercial multi-mode microwave ovens designed for these purposes.

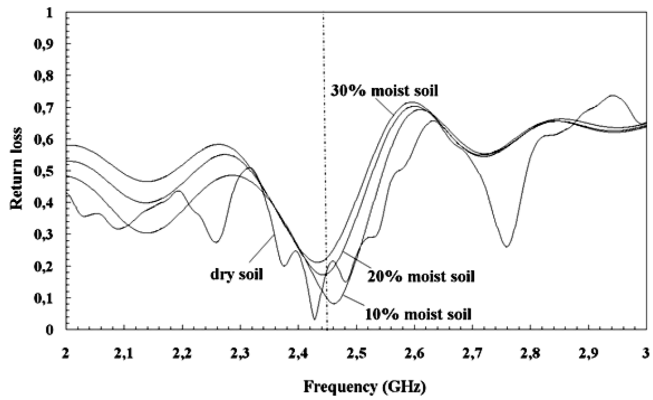


**Figure 2.** Reflection properties of microwave antenna

Different single-mode and multi-mode microwave heating systems find wide practical application in analytical chemistry[5]. The repeatability of chemical reactions is one of the main requirements for such systems. That is, quite uniform distribution of power density and temperature in an interaction domain must be achieved. Single-mode waveguide and resonator cavities, intended for heating of only one sample, usually satisfy this requirement. In multi-mode cavities, where several samples are heated, the problem of non uniform distribution of power sources is solved by rotating the samples.

Almost all microwave chemistry applicators are designed on a basis of rectangular or cylindrical waveguides and cavities. The so-called reentrant cavity with extended capacitance gap has been proposed[6] as a basic unit of microwave chemistry applicator, as shown in Fig. 3. This resonator has higher values of resonance wavelengths of the dominant mode than simple reentrant cavity well known in microwave electronics. The last feature allows us to select the operating frequency 915 MHz, and, consequently, to increase EM field penetration depth in lossy dielectric.

The dominant mode in the cavity is excited by a coaxial probe on a central axis. The glass test tubes with liquid samples (water, protein and pyrrolidin) are arranged around the probe in capacitance gap in a special ring-shaped Teflon holder.

The coupled problem was solved in the present study by using the FEM and commercial software COMSOL. One more numerical technique, the FDTD method implemented in another commercial code QW3D was employed to find cavity sizes, which provide the best coupling at operating frequency.

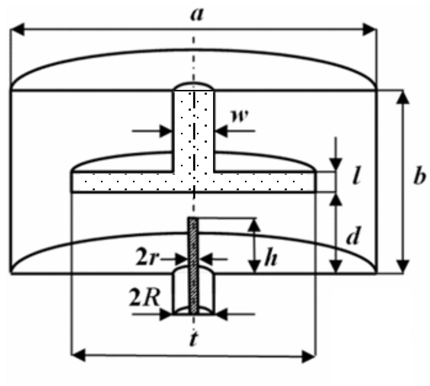


**Figure 3.** A microwave chemistry reactor design, $a = 210$ mm, $b = 105$ mm at 915 MHz.

Simulations have demonstrated that the best coupling is observed for water at 60°C. It is interesting to note, that the reflection coefficient values are the same for temperatures 40°C and 80°C at 915 MHz. Slightly higher reflection has been achieved for protein. Simulations of the microwave applicator with 8 pyrrolidin samples have shown an almost complete reflection of EM power. But, as it has been proven numerically, coupling can be improved in this case by changing the capacitance gap sizes.

Figure 4 illustrates temperature field pattern in four water samples. Given solution of a coupled problem did not include convection processes, and in reality microwave heating of liquid samples with low viscosity will be much more uniform.

### *Tumor ablation*

As it is known microwave energy is widely used in medicine. For example, it can be a very promising tool for tumor ablation. Malignant biological tissues during microwave ablation (MA) are heated up to relatively high temperatures (60…100ºC) in order to achieve coagulative necrosis of tumor cells. This minimally invasive procedure provides less bleeding, possibility of using local anaesthesia and other advantages in comparison with conventional approaches. Cancerous tissues are heated up to high temperatures using, for example, a coaxial antenna[7] as presented in Figure 5.

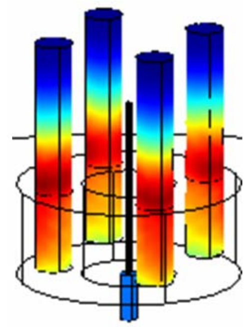

**Figure 4.** Temperature distribution in water samples heated in a cavity such as shown in Fig. 3. The tube diameter and height are 10 mm and 50 mm, respectively. The temperature varies along the tube from 20ºC (Dark Blue) to 81ºC (Red).

The radiating part of this antenna is inserted in the middle of tumor zone. Antenna diameter is less than 2 mm, and the operating frequency is 2.45 GHz. The space between coaxial conductors is filled with Teflon. Cone shaped component made of ceramics protects the thin probe from damage, and provides low level of reflected power during microwave ablation. The necessary temperature in the biological tissue is controlled by special remote system.

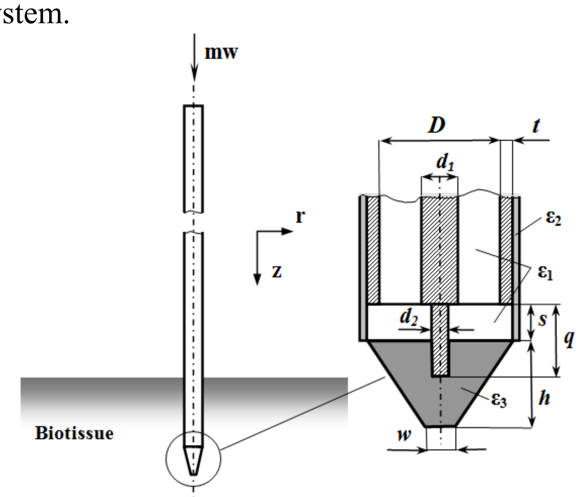


**Figure 5.** Microwave tumor ablation antenna (of less than 2-mm diameter)

Preliminary experimental studies on phantom models of biological tissues, such as muscle, liver and brain, have shown relatively low level of reflected power for this antenna (less than 3%) at operating frequency 2.45 GHz. Then, temperature patterns have been simulated by FEM in the ablation zone. The coupled EM-bioheat problem was solved employing COMSOL software, and besides, temperature dependencies of the tissues dielectric properties were taken into account.

Reflection characteristics of the antenna have been simulated and optimized by means of the QW3D software.

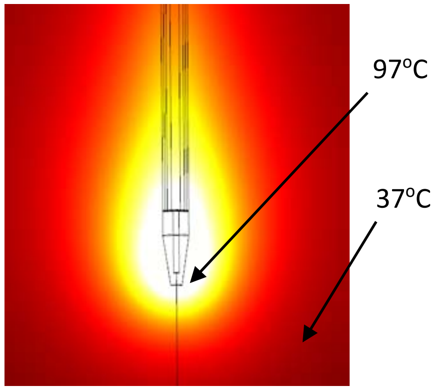


**Figure 6.** Temperature distribution in liver.

The computed results allow to estimate the electromagnetic and thermal characteristics of the interstitial coaxial antenna of 2.45 GHz at different temperatures during the MA procedure. Such antenna shows relatively low values of return loss at body temperature for various biological tissues, such as muscle, liver, kidney and brain, and increasing the reflected power up to 9 – 25 % at high temperatures in the range $80 \leq T$ [ºC] $\leq 100$ for liver. But, even in the worst case ($T$ = 100ºC), the antenna delivers 75% of microwave energy to the tissue. Figure 6 shows the temperature patterns after 6 minutes of heating at 10 W. The lesion domain radius and sphericity are $R_l$ = 7.6 mm and $W_s$ = 0.34, respectively.

### *Summary*

The three examples presented above illustrate powerful capabilities of the commercial codes COMSOL and QW3D for comprehensive analysis and optimization of industrial, scientific and medical microwave systems (as shown in Figs. 1, 3 and 5, respectively). The application of two numerical approaches in parallel allows increasing the efficiency and flexibility of the mathematical modeling of microwave heating processes, when the disadvantages of one method are compensated by the advantages of the other, and vise versa.

## For further reading:

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## About the Author

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