Finite Element Modeling of Electromagnetic Field in an Experimental RF Heating System

Vyacheslav Komarov[1,2], Juming Tang[1] and Shaojin Wang[1]

[1] Microwave & RF Heating Group, Biological Systems Engineering Department, Washington State University, Pullman, WA

[2] Department of Electronic Engineering & Instrument-Making, Saratov Polytechnic Institute, Saratov, Russia

vkom@mail.saratov.ru

This research was supported by:

- USDA-IFAFS
- USDA-CSREES, and
- BARD (The US-Israel Bi-National Agricultural Research Development Fund).

Microwave and RF Heating Group

Electromagnetic Processing of Agricultural Products

- Insect pest infestation of commodities is a major problem in the production, storage, marketing and export of agricultural products.
- Methyl bromide and other chemicals are used today to fumigate these commodities.
- Application of high frequency electromagnetic energy may be an attractive alternative to conventional methods of treatment.
- ISM frequencies: f = 13.56 MHz, 27.12 MHz and 40.68 MHz (RF range) and f = 915 MHz and 2450 MHz (microwave range) are allowed for these purposes.
- RF radiation provides deeper penetration of EM fields in lossy media than microwave one.

Electromagnetic Processing of Agricultural Products (cont’d)

- Uniformity of RF heating can be improved by full immersion of fruits in water.

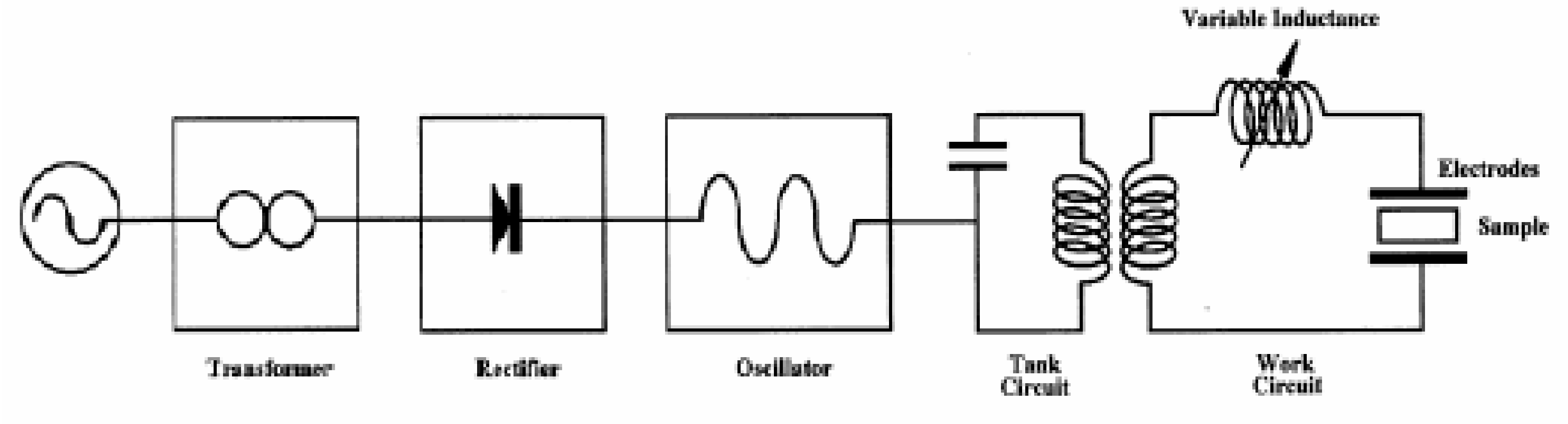
  The objective of this research was to evaluate a feasibility of combining an immersion technique with RF energy.

- Computer modeling of EM fields allows to decrease experimental expenses.

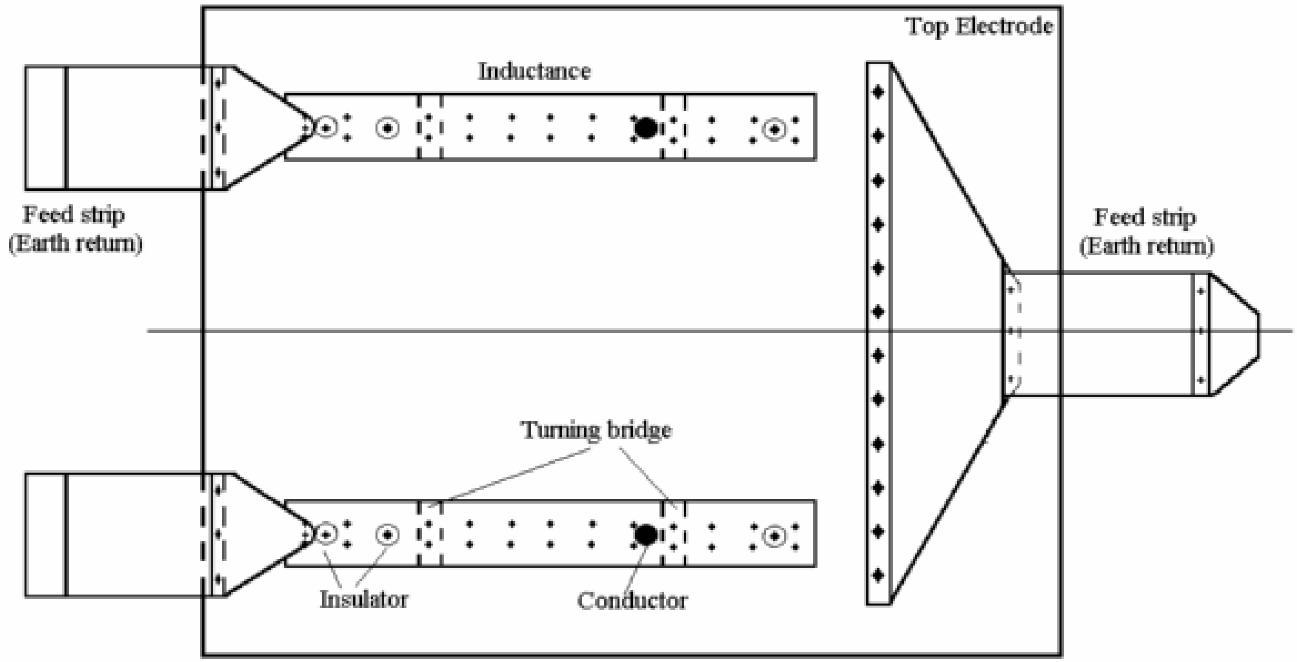
Experimental RF Heating System Used in WSU

- Experimental studies of this technology are carried out in Washington State University with the help of a 6 kW, 27.12 MHz pilot-scaled RF system (COMBI 6-S, Strayfield-Fastran Ltd., UK).
- The RF system comprises a transformer, rectifier, electronic oscillator, and inductance-capacitance pair (tank circuit), and the working circuit made up of the applicator and the material to be treated.
- The parallel plate electrodes with sample placed on the lower electrode (tray base) acts as a capacitor in the working circuit.
- Height of the top electrode is adjustable to change the effective capacitance and the amount of RF power coupled to the sample;
- Plastic container filled with tap water is used for preliminary studies of E-field uniformity in an interaction zone.

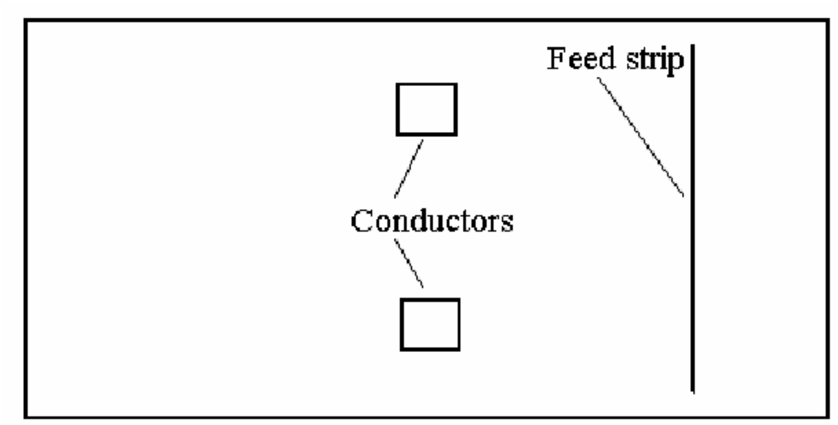
Schematic Diagram of the RF System



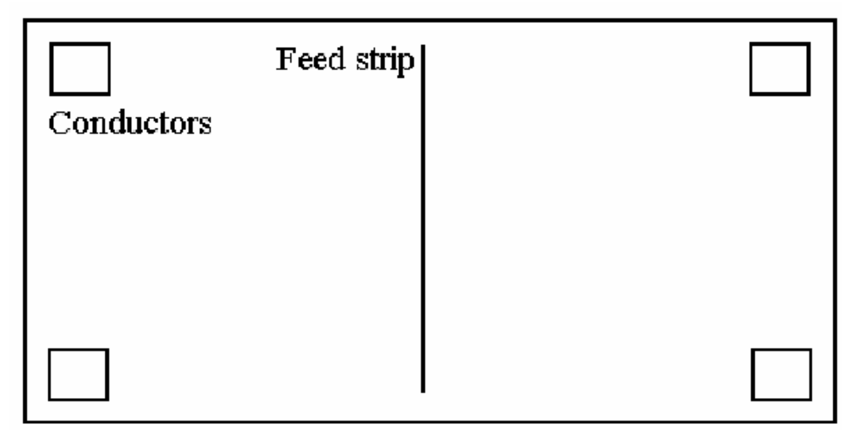
Top Electrode Design of the Original RF System



Placement of the Feed Strip and Conductors in Original (a) and Upgraded (b) Electrode of the Experimental RF System



a

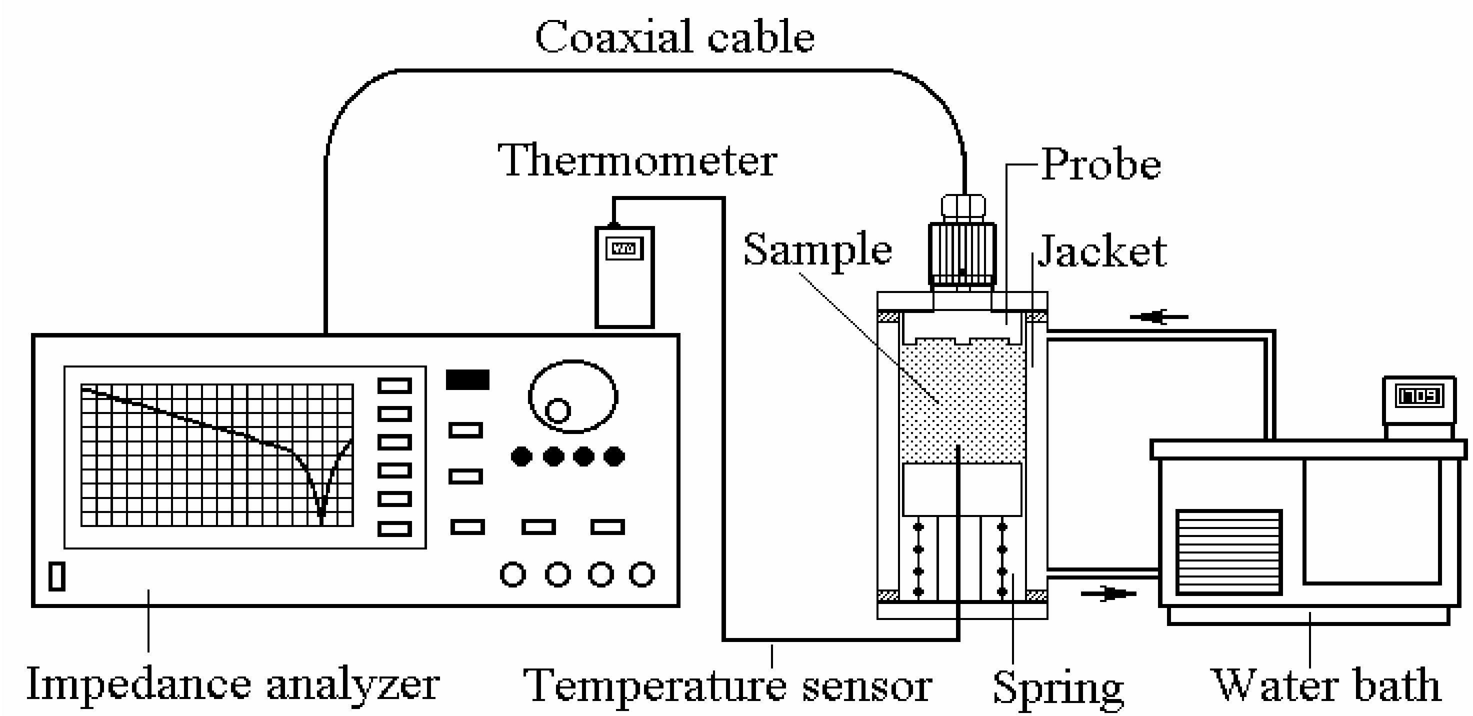


b

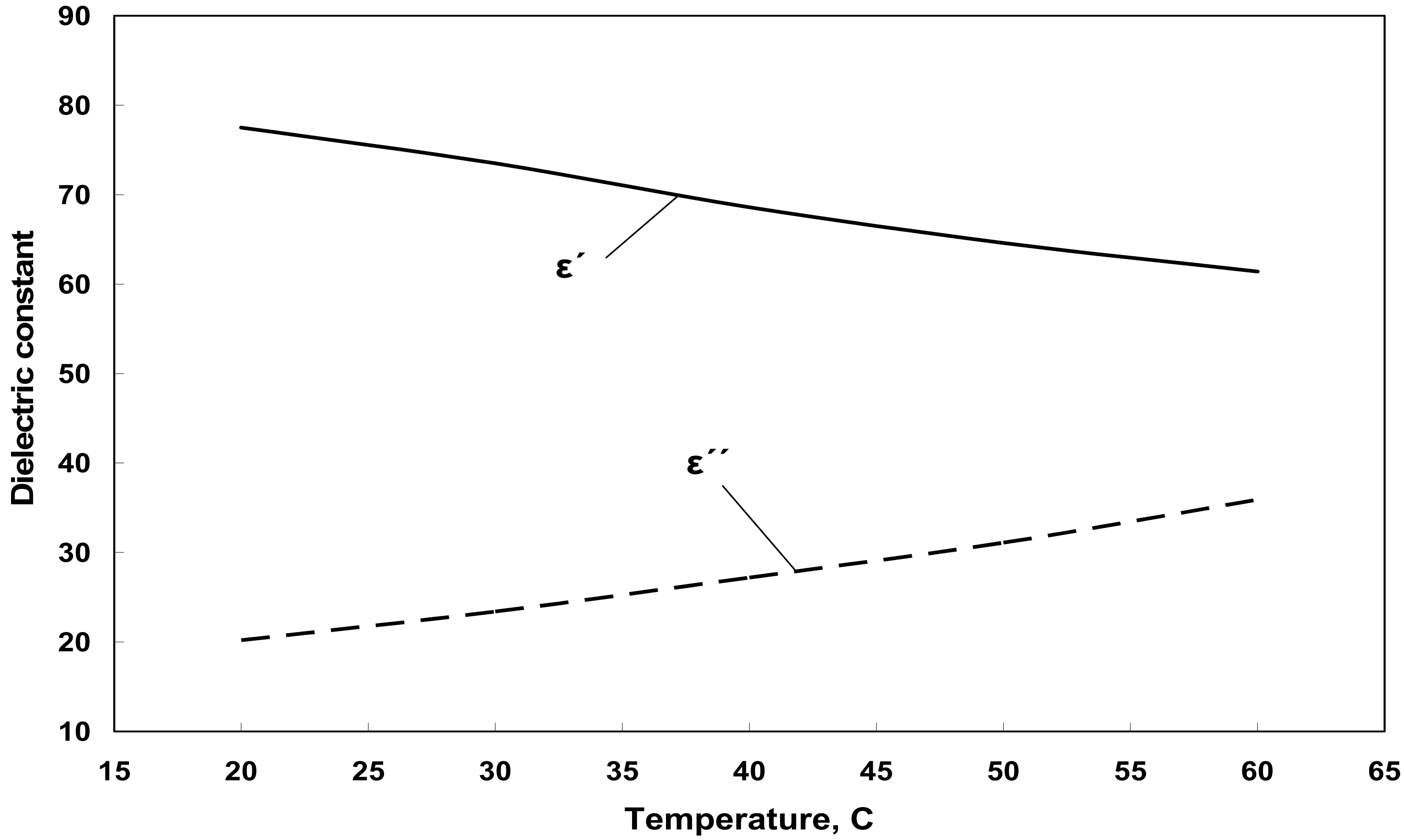
Measuring Dielectric Properties of Tap Water at 27.12 MHz

- Open-end coaxial probe method is currently one of the most popular techniques for measuring of complex dielectric permittivity of many materials.
- Coaxial probe system used at WSU consists of a Network Analyzer with a calibration kit, custom built test cell, a programmable circulator, a coaxial cable and a PC connected to the NA.
- The material under study is placed in a steel pressure-proof test cell, and the programmable circulator pumps a temperature controlled liquid (90% ethylene glycol and 10% water) through the water jacket of the test cell, allowing the sample inside to be heated and cooled.
- Parameters (amplitude and phase) of incident and reflected signals are detected by the Network Analyzer.

Open-Ended Coaxial Probe Measurement Setup



Dielectric Properties of Tap Water at 27.12 MHz



Basic Differential Equations and Boundary Conditions

3D Quasi-static application mode for the case of time-harmonic EM fields and currents.

Basic equation: $$j\omega\sigma\tilde{\mathbf{A}} + \nabla\times(\mu^{-1}\nabla\times\tilde{\mathbf{A}} - \mathbf{M}) - \sigma\mathbf{v}\times(\nabla\times\tilde{\mathbf{A}}) = \mathbf{J}^e \quad (1)$$

$$\tilde{\mathbf{A}} = \mathbf{A} - \frac{j}{\omega}\nabla V \quad (2) \qquad \mathbf{E} = -\nabla V - \frac{\partial \mathbf{A}}{\partial t} \quad (3)$$

Boundary conditions: $$-\mathbf{n}\times\mathbf{H} + \frac{K}{\mu_0}\mathbf{n}\times(\mathbf{A}\times\mathbf{n}) = \frac{K}{\mu_0}\mathbf{n}\times(\mathbf{A}_0\times\mathbf{n}) \quad (4)$$

$$V = V_0 \quad (5) \qquad V = 0 \; ; \; \mathbf{n}\times\mathbf{A} = \mathbf{0} \quad (6)$$

Finite Element Modeling of RF Applicator Using FEMLAB v. 2.3a

- The only known 3D numerical modeling of RF heating systems is the work by Neophytou and Metaxas. They used their own FE code for simulation resonance frequencies and fields (in an RF applicator at 27.12 MHz);
- Formulated EM problem in principle can be solved using some commercial packages (e.g., HFSS (3D FEM) and QW3D (3D FDTD)), which however are more expensive than FEMLAB. Moreover, HFSS requires *more computer memory* than FEMLAB, and application of QW3D for problems with this type of *sources* is problematic.
- FEMLAB is a multifunctional program providing FE solution to Maxwell's equations in a wide frequency range. FEMLAB's Model Library contains an example of modeling of RF capacitor in electrostatic mode – this helped us to understand some peculiarities of FEMLAB application to such EM systems.

Main Finite Element Modeling Steps

Step 1. Geometrical modeling. Application of embedded zero-thickness elements for simulation of electrodes, feed strips and conductors.

Step 2. Specification of boundary conditions: E-potential, ground and electric insulation.

Step 3. Specification of magnetic, electric and dielectric properties of materials in subdomains.

Step 4. Assigning operating frequency 27.12 MHz and voltage (3 kV).

Step 5. Mesh generation using Lagrange or vector finite elements.

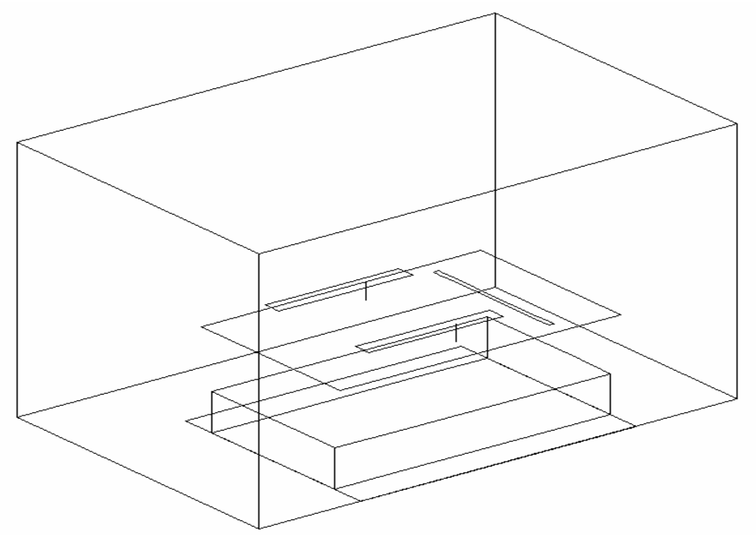
Step 6. Choosing a stationary linear solver for matrix equation.

Step 7. Visualization of simulation results.

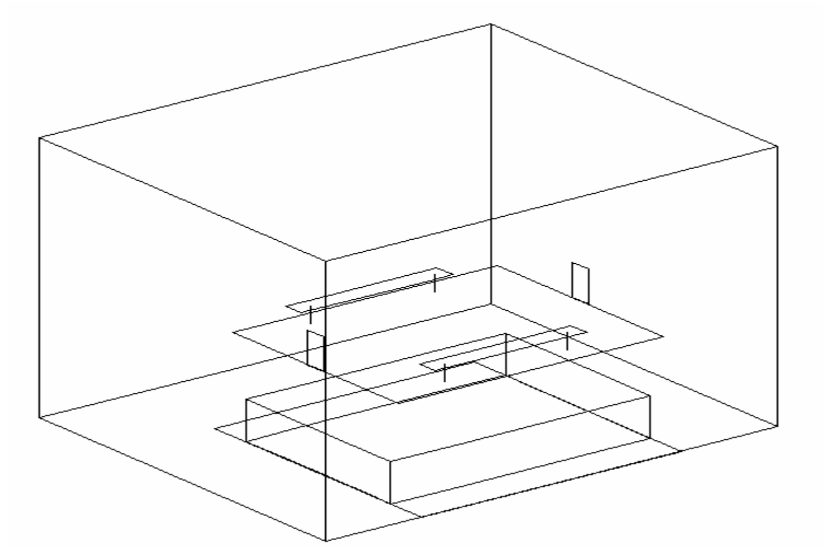
Microwave and RF Heating Group

All steps are performed by means of flexible Graphical User Interface (GUI) implemented in FEMLAB

Geometrical Model of Original (a) and Modified (b) RF Applicator

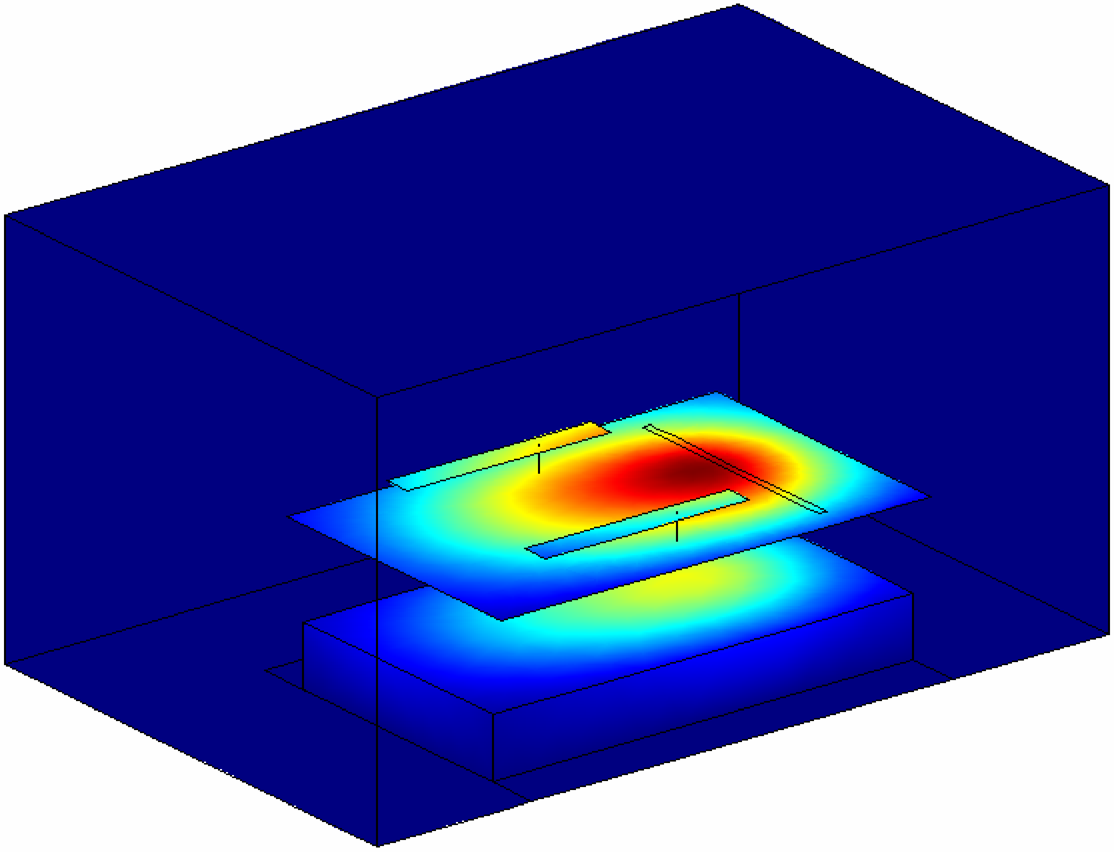


a



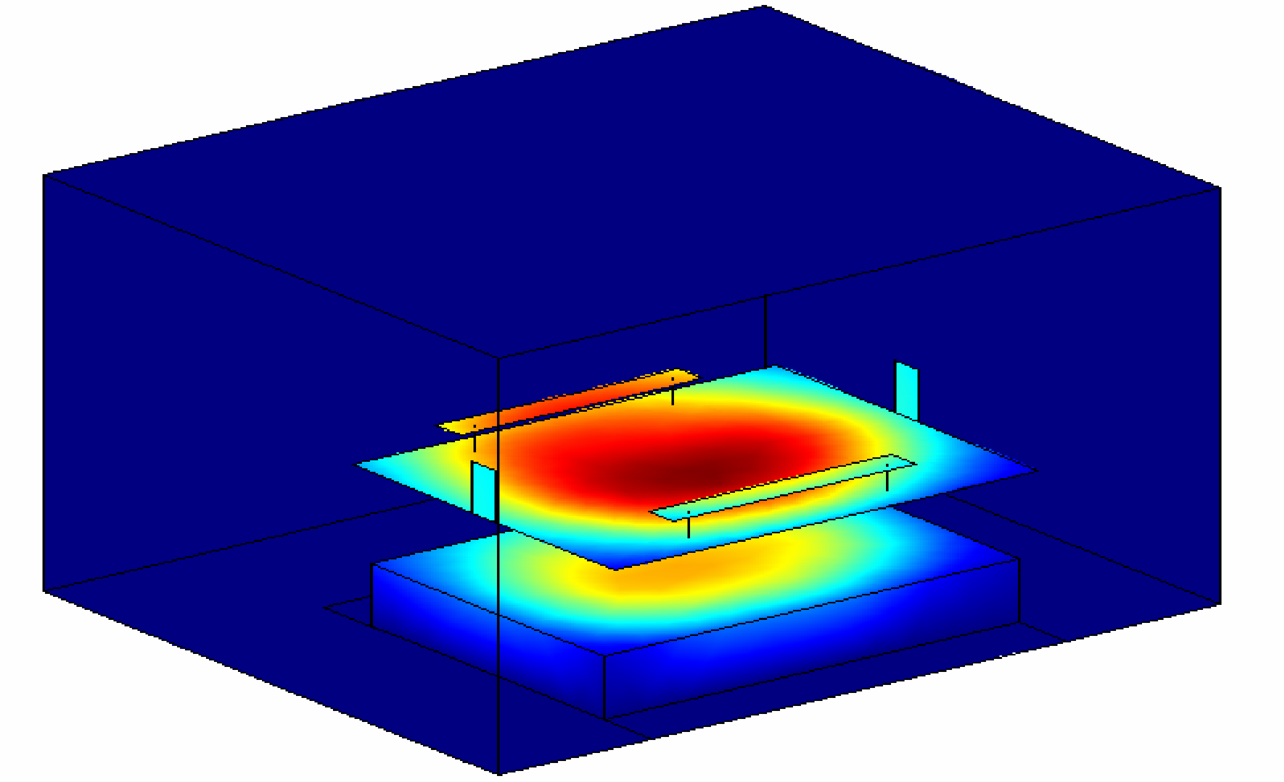
b

Electric Voltage Distribution in the Original RF System



Microwave and RF Heating Group

Electric Voltage Distribution in Modified RF System



Microwave and RF Heating Group

Conclusion

- Commercial code FEMLAB version 2.3a can be successfully employed for modeling EM fields in the RF heating systems.
- 3D Quasi-static application mode is preferable for this purpose.
- The example considered in the paper has been solved using a PC with 250 MB RAM; simulation time: less than 15 minutes.
- Experimental measurements have confirmed the pattern of the E-field distribution in container filled with tap water at 27.12 MHz.

Acknowledgement

Authors are grateful to the Support Group members of Comsol Inc. for their help in development of the FEMLAB model.