

COMSOL Multiphysics in Undergraduate Education of Electromagnetic Field Biological Interactions

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Abstract — In this paper we present a basic model created in COMSOL Multiphysics for undergraduate education purposes in courses dealing with biological effects of electromagnetic fields, electromagnetic fields in biological systems. COMSOL Multiphysics provides possibility to combine various physical processes described by differential equations to one simulation. Easy-to-do and attractive graphical post-processing of the calculated results in COMSOL Multiphysics are very useful for presentation in classroom and lecture what increases students' interest in the subject as well as their attention.

Keywords — COMSOL Multiphysics, undergraduate education, bioelectromagnetics, microwaves, hyperthermia

INTRODUCTION

Application of simulation software based on various mathematical methods (FEM, FDTD, etc.) for modeling of various physical processes for research and education purposes has grown rapidly in recent years. Although researcher is able to solve various problems analytically or using various approximations, when the problem becomes too complex, he needs to use numerical calculations to obtain a solution. Nowadays, enough computer power is usually available for calculation of common problems. A substantial amount of the problems can be solved numerically when one, after understanding physical background of the problem, writes suitable script in programming language of his choice. However, in many cases this is too time consuming or demanding on programming skills. Thus, one reaches for one of the various simulation softwares, which are nowadays available commercially. It is reasonable considering that programming team containing number of software engineers are able to do more than a single researcher who needs to deal with many other tasks than programming of his tools. Software groups focus on specialized problems and as a team they can provide high valued product which saves the time of the researcher. Similar reasoning can be used in the field of undergraduate education.

Research and education interests of authors of this paper are industrial and biomedical applications of microwaves, effect of electromagnetic field on biological systems and

generation of electromagnetic field in biological systems. All topics include theoretical treatment of the problems, numerical and experimental verification of theoretical results. Parts of physics that needs to be covered range from electromagnetics, thermal physics – heat conduction, conduction and radiation, mechanics, stress and strain to chemistry and biophysics, prospectively. In order to provide interactive undergraduate education in these topics, one needs simulation software that fulfills several prerequisites. Software needs to be:

- user friendly and easily controllable
- able of multiphysical simulations
- able of easy-to-do and illustrative graphical visualization of results.

COMSOL Multiphysics[®] fulfills these prerequisites. It is finite element based unifying multiphysical simulation environment. The COMSOL Multiphysics[®] [4] (abbr. “COMSOL” in further text) simulation environment facilitates all steps in the modeling process - defining the geometry, specifying the physics, meshing, solving and then post-processing the results. Model set up is quick, thanks to a number of predefined modeling interfaces for applications ranging from fluid flow and heat transfer to structural mechanics and electromagnetic analyses. Material properties, source terms and boundary conditions can all be arbitrary functions of the dependent variables. Application-specific modules bring terminology, material libraries, solvers and elements, as well as visualization tools appropriately specialized to the application area. In addition to custom solutions, each of the add-on modules comes with a large number of ready-to-run and well-documented example models. Except the multiphysical core, COMSOL includes several modules which cover most fields of physics.

However, one is not limited by these modules. Problem can be described by partial differential equations (PDE) from scratch. PDEs can be also added to the existing module to make the model more precise in description. Although we can easily handle the physical problems using the modules, we do not lose contact with the physical description, since the PDE in actual form is visible whenever setting the subdomain, boundary or edge properties.

We focus in this paper on exemplary model of microwave applicator used in microwave hyperthermia. This model is easily constructed and shows advantages of COMSOL in multiphysical modeling in undergraduate education.

MICROWAVE HYPERTHERMIA

Microwave induced hyperthermia represents an important tool in anti cancer treatments, both as an adjuvant of chemo and radiation therapies and as an ablative procedure, according to the type of applicator used. When the temperature of a part of the body is enhanced over 3 °C above its normal value, the cells start to be under thermal stress. Going above 41.5 °C this stress begins gradually to induce irreversible damages like cell apoptosis and necrosis, whose extent is inversely proportional to the ratio heat intensity over time. For this reason, commonly in clinical practice, the temperature in the tumour is enhanced in the range 41.5-45 °C for a period of about 30-60 minutes.

Microwaves can induce effective and quite homogeneous hyperthermia, associated to direct effects on cellular molecules and H₂O.

Effective delivery of microwaves depends on precise characteristics of microwave applicators which must be able to focus the electromagnetic energy as much as possible in the cancer tissue in order not to damage the surrounding healthy tissue. In any case, temperature enhancement produced by microwave radiation induces blood perfusion changes [1] which increase heat conduction in healthy tissue producing a selective increase in tumour temperature providing an effective heat trap. In fact, when the temperature is enhanced, blood flow enhances as well, acting as a

cooler. Since the vascular system of tumours is generally irregular and incompletely developed, this cooling effect is thereby lower than in normal tissues. In these conditions, on equal electromagnetic energy exposure, the temperature inside the tumour will be maintained higher with cumulative effects [2].

Hyperthermia is newly back in the interest of both, clinical and research oncologists, because of its properties to directly produce permanent damages of the treated tumour and to elicit important immunological responses against cancer cells by changing their immunogenicity [3].

MODEL

Microwave applicator suitable for hyperthermia needs to be properly designed in order to deliver electromagnetic energy into the tumor tissue with minimal irradiation of healthy tissue. This can be tuned by optimal radiation pattern of the applicator and water bolus which is used to cool down the surface of the tissue - skin. We will show exemplary design of the microwave patch applicator for frequency of 2.45 GHz. We will not treat underlying antenna theory, it can be found in standard antenna textbooks.

We will first draw the geometry of the problem. One of the advantages of COMSOL compared to other modeling software, even specialized on electromagnetics and radiofrequency modeling, is possibility to exploit axial symmetry of the problem. This enormously saves computer power and requirements on the memory by modeling in 2D instead of 3D. Geometry of the model is shown in the Fig. 1.

We create simple yet multiphysical model consisting of electromagnetic and heat transfer part. After drawing the model, one needs to define the physics of the model. This is done separately for electromagnetic and heat part, setting material properties of subdomain and boundary settings. Depending on the character of the boundary or the subdomain, corresponding equation describing the problem is displayed. If calculation in any subdomain is not desired, it can be excluded. Here, we are not interested in temperature of the water bolus. In praxis, water in the bolus is circulated and cooled to keep it at the same temperature. We approximated it in our model by setting the temperature of the water bolus-tissue boundary to constant 20 °C. Tissue is approximated to be homogenous in both electromagnetic and heat domain. Electromagnetic energy is transformed into the heat in the tissue since the tissue lossy. Coaxial cable is fed by 50 W via "Port" setting.

Bioheat equation is used for description of blood perfusion of the tissue. The coupling of the electromagnetic and heat path is done simply by including the external (spatial) heat source in bioheat equation (see Fig. 3). The external

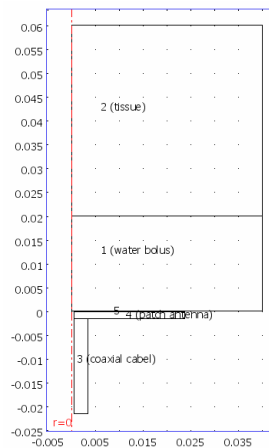


Fig. 1 Model drawn using axial symmetry, red line is symmetry axis. Dimensions are in meters. Subdomains labeled.

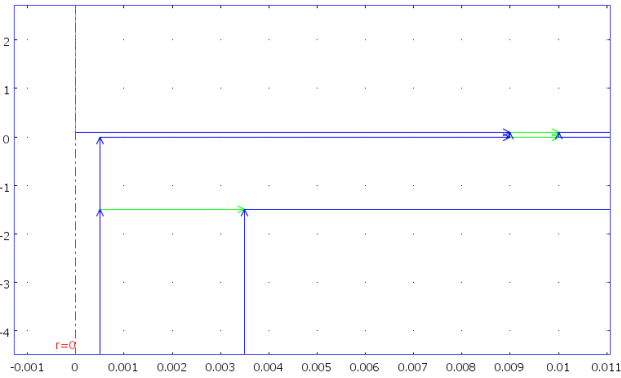


Fig. 2 Detail of the slot of the patch applicator. Dimensions of x and y axis are in meters and millimeters, respectively. Boundary mode displayed – blue lines represent perfectly conducting material (PEC), green lines are continuities.

heat is set to originate from the electromagnetic energy transformed into heat due to nonzero conductivity of the tissue. Coupling is done via variable Qav_rfweh.

After the setting geometry and physics, we create a mesh which discretize the problem. Meshing can be done automatically. Additionally, various settings can be tuned manually or semi-automatically (e.g. mesh elements, element growth factor) to create a mesh which is reasonable fine for the given purpose and still not too large to be solvable with available PC.

Afterwards, we can start solving the problem. COMSOL has several solvers available to cope with various problems. Many solver settings can be changed manually. Firstly, we need to solve the electromagnetic part. It is independent from the heat part, since we assume that electric parameters

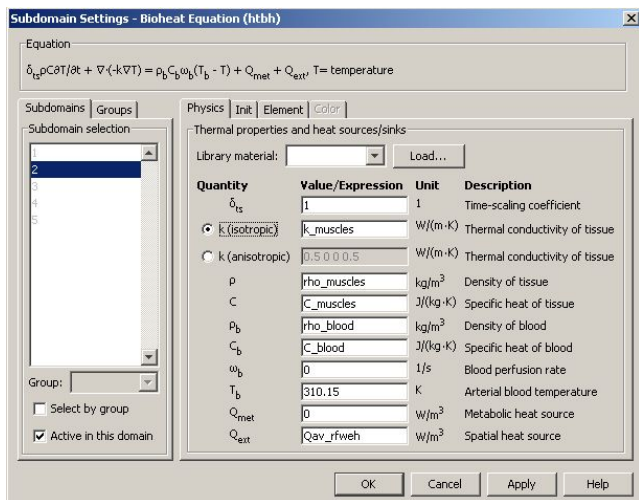


Fig. 3 Example of subdomain settings (subdomain 2 - tissue). Bioheat equation is a part of heat transfer module.

Table 1 Font sizes and styles

| Description | Value |
|-----------------------------------|-----------------|
| Thermal conductivity, muscle | 0.56 [W/(m*K)] |
| Density, blood | 1e3 [kg/m^3] |
| Specific heat, blood | 3825 [J/(kg*K)] |
| Specific heat, muscle | 3639 [J/(kg*K)] |
| Blood perfusion rate | 3.6e-3 [1/s] |
| Blood temperature | 37 [°C] |
| Relative permittivity, dielectric | 4.3 |
| Relative permittivity, catheter | 77.6 |
| Relative permittivity, muscle | 53 |
| Electric conductivity, muscle | 1.73 [S/m] |
| Electric conductivity, water | 1.26 [S/m] |

of the tissue will not change with the temperature. With the automatic extra fine meshing (2 level above normal meshing) the mesh will consist of ca. 20 thousand elements, the solution of the electromagnetic and heat problem is done in 62 seconds (PC 3 GHz, Intel Pentium 4, L2 1MB, 1GB RAM).

Constants used for the material properties are in the Tab. 1

In some cases when the physical problems are inter-coupled, we need to solve for one single physical problem first, and then set it as initial conditions for the solution of multiphysical problem.

The solution is automatically plotted taking the default post-processing settings. The last step is to choose a proper quantity (or few of them) to be displayed. We show the calculated electric field and temperature distribution after 10 minutes of heating on the Fig. 4.

The immediate results show where the electrical power is focused. Most power is dissipated in water bolus. However,

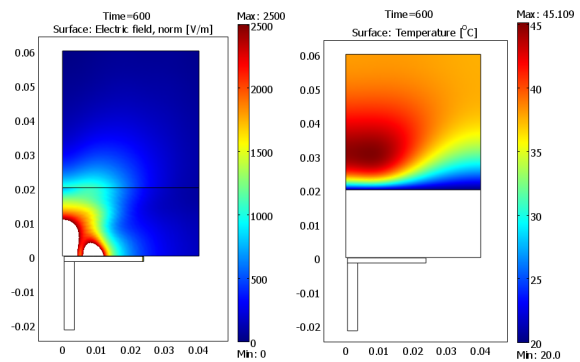


Fig. 4 left: Electric field distribution, white spaces are above displayed range (2500 V/m); right: Temperature distribution after 600 s of heating. All axes in meters

since circulation of water, here expressed by constant temperature of water bolus-tissue boundary, ensures the cooling of the tissue surface, the focused hotspot lies under the surface of tissue.

DISCUSSION & CONCLUSION

We have shown basic steps in modeling a microwave patch applicator for heating of tissue. The drawing of geometry of problem with setting of the physics can be done within several minutes, depending on the experience of the user. Automatic meshing followed by solving takes few minutes. Post-processing of the data and exporting of image is a matter of few minutes as well. If we want to produce an animated result, what can be done in our case (we calculated temperature evolution from 0 to 600 s) it may take several minutes, depending on the desired quality and frame rate of the movie. This is of great help not only in education but also in research presentation.

Regarding model shown in this paper, we could introduce relatively easily various enhancements to make it more corresponding to reality. We could simply introduce more layers of the tissue: several levels of skin, fat layer, even bone, if necessary. Further it would be reasonable to use other electrical and heat conduction properties for tumor tissue. Tumors have usually different structure and lower blood perfusion, depending on the type.

Computer aided design often includes optimization of various parameters. This can be done in COMSOL as well, either by using built in COMSOL scripting language or by exporting the model into MatLab m-file and running the model with various sweep parameters in cycle. Since MatLab is a standard engineering tool, easy export of a model into MatLab is very welcome.

COMSOL provides extensive manuals for every module and feature. There are also plenty of sample models available in model library. These models are freely editable and can serve as a base for inspiration and learning. For one from many see Fig. 5, which depicts specific absorption ratio (SAR) on human head caused by irradiation by patch antenna.

We would like to conclude that a COMSOL Multiphysics® fully fulfils the needs of educator and researcher providing him a tool which is not only easy to use (compared to other multiphysical tools) yet complex and universal but also capable to create attractive presentation of results.

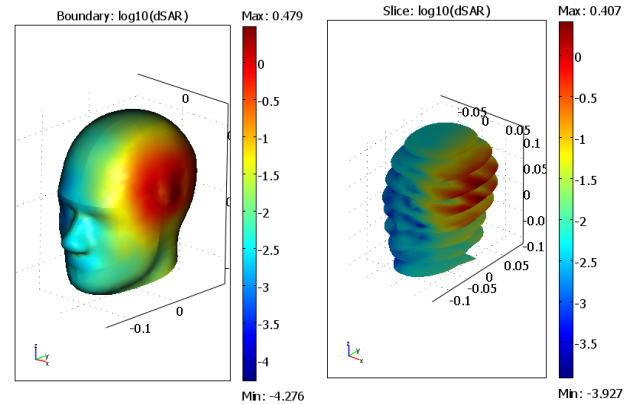


Fig. 5 left: SAR distribution on the boundary, right: SAR distribution on the slices. Axes in meters, SAR logarithmic

Regarding the undergraduate education, it will inevitably increase the interest of students by dragging them near to the research topics in visually appealing form.

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