Electromagnetic field computations for saturated porous media

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Introduction: The multi-physical environment of COMSOL makes attractive to model physical phenomena of particular interest coupled to a petroleum related application [1] (cf. Fig.1). Mention a successful and promising examples of the resistive-heating assisted bitumen recovery [2] and the EM-heating method for in-situ upgrading [3].

Relatively simple geometrical configurations have been used to validate our models using comparison to available and developed analytical solutions. The examples of EM field computations are presented with detailed analysis of numerical solution accuracy and computational performance of the model. The advantages of latest COMSOL versions (both elements choice and solver features) are concluded.

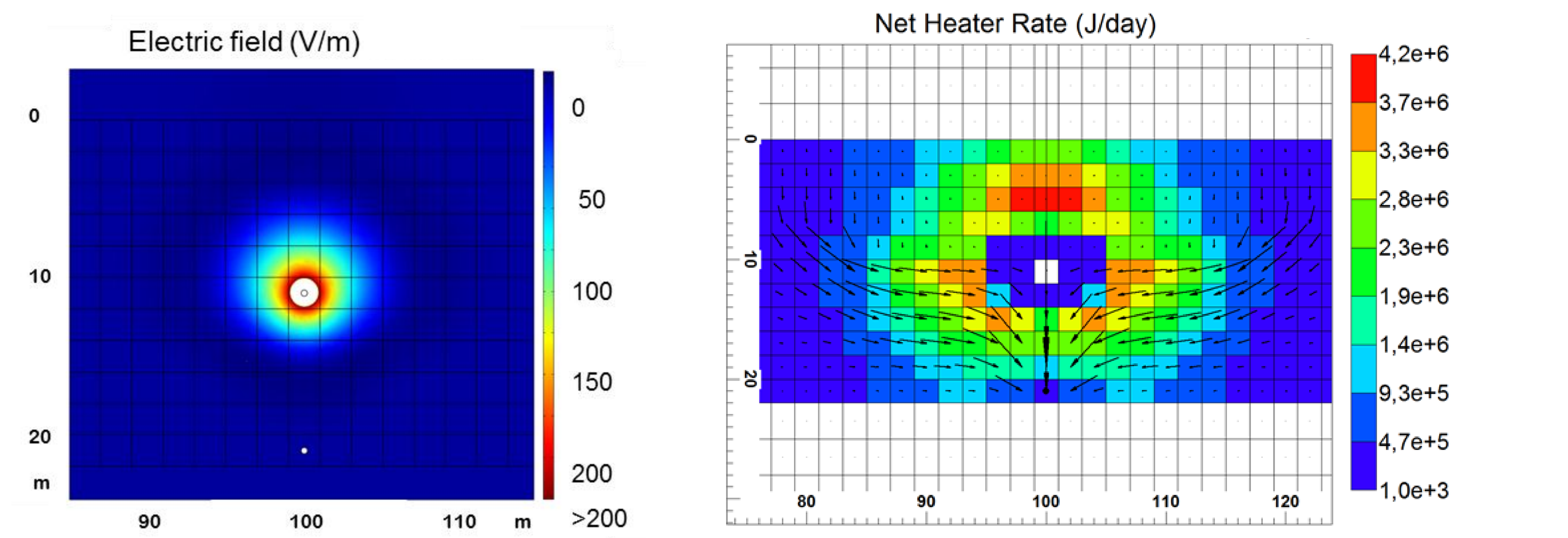

Figure 1. Electric field magnitude (left); power field and oil local velocity (right) computed per reservoir simulator grid block.

Model formulation: Time harmonic Maxwell's equations in their second order form (1) are used. To represent the antenna conditions, a magnetic field boundary condition (2) and, for unbounded domain, absorbing boundary condition (3) are applied.

$$\nabla \times \mu_r^{-1}(\nabla \times \mathbf{E}) - k^2\left(\varepsilon_r - \frac{j\sigma}{\omega\varepsilon_0}\right)\mathbf{E} = 0, \qquad (1)$$

$$\mathbf{H} = \mathbf{H_0}, \qquad (2)$$

$$\mathbf{n} \times (\nabla \times \mathbf{E}) - \mathrm{jk}\,\mathbf{n} \times (\mathbf{E} \times \mathbf{n}) = 0. \qquad (3)$$

RF test on a 1D radial model: Two homogeneous and connected subdomains are considered as follows:

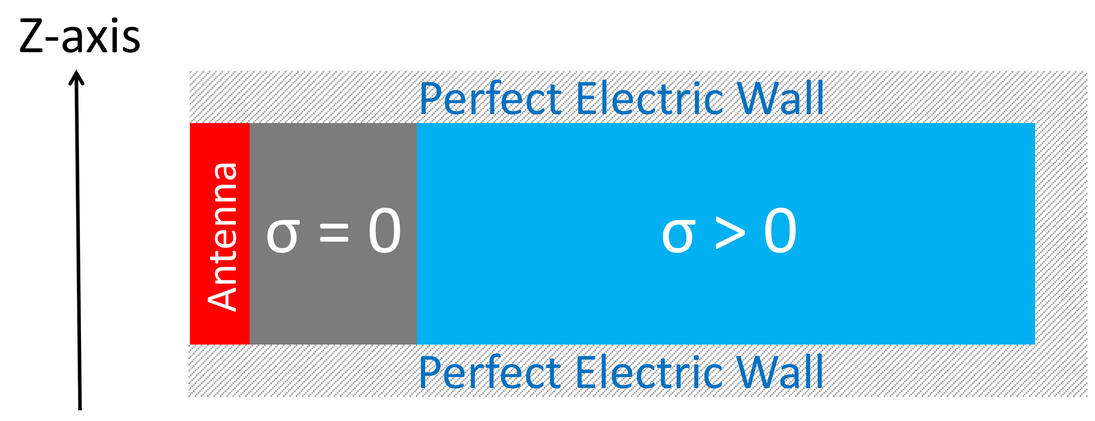

Figure 2. Test geometry.

Locally on each subdomain, $\mathbf{H}_0 = H_0 \cdot \mathbf{e}_\varphi$, then the azimuthal field component satisfies the equation

$$\frac{\partial^2 H_\varphi}{\partial r^2} + \frac{1}{r}\frac{\partial H_\varphi}{\partial r} - \frac{1}{r^2}H_\varphi + k^2\,\varepsilon_r\,H_\varphi = 0 \qquad (4)$$

and at a property interface (cf. Fig.2),

$$[H_\varphi] = 0 \ \text{ and } \ \left[\varepsilon_r^{-1}\left(\frac{\partial(rH_\varphi)}{\partial r}\right)\right] = 0 \qquad (5)$$

Results: Performance and accuracy of COMSOL have been tested. The results below (Figs.3-5) make comparison of different COMSOL versions and exact solution of (4-5).

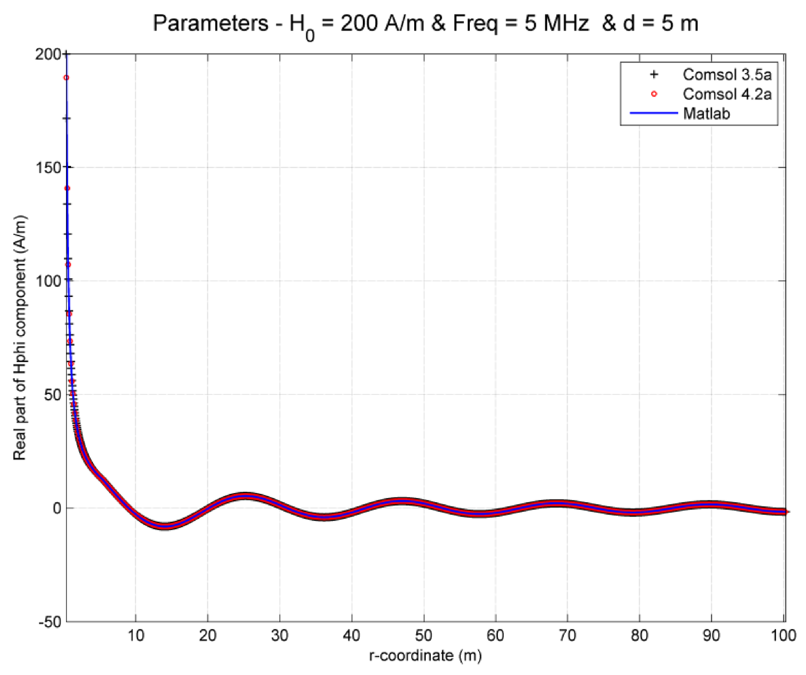

Figure 3. Real part of H_φ .

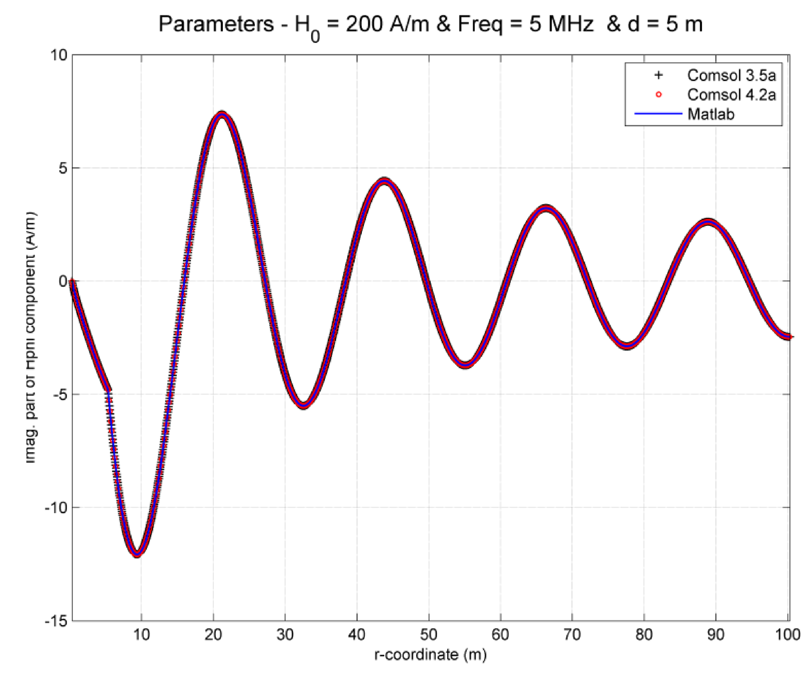

Figure 4. Imaginary part.

Our major interest in EM heating problems is to determine the heating power integrated over model subdomain (cf. below).

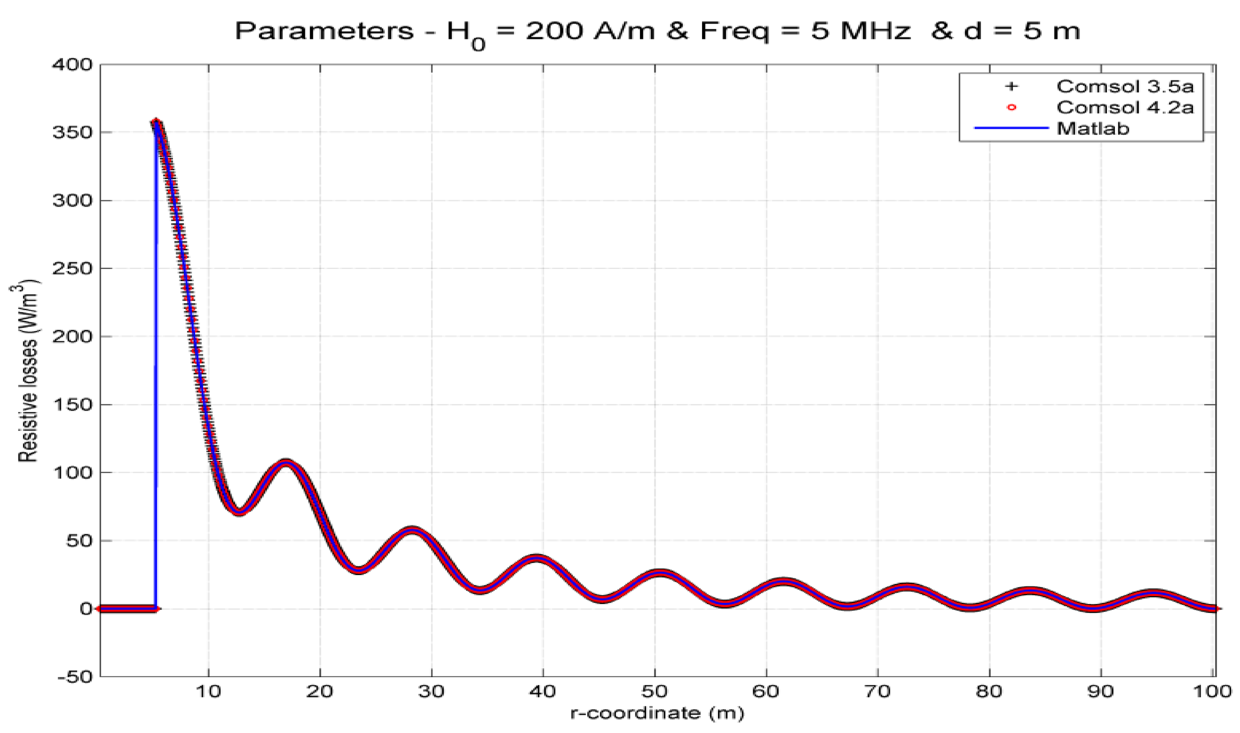

Figure 5. Heating power field comparison.

Although each tested version of COMSOL give a good results, we concluded in particular that the versions 4.2x demonstrated a better convergence rate.

Conclusions: Local electromagnetic power computations in heterogeneous reservoir is a challenging problem for petroleum applications;

Multi-domain models are well-suited for our purposes and may be successfully adapted for the power field determination;

COMSOL version 4.2 based RF-field models can be used for variable electric properties in saturated porous media.

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References:

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