High-Frequency Electromagnetic Heating: 3D Model for Petroleum Production Applications

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Abstract: Oil production industry is currently investigating new methods to improve oil and gas extraction from natural rocks. Since long time the dedicated simulation software has been used to better understand the behavior and predict the production from oil and gas reservoirs depending on developed technologies. Modern reservoir simulators are capable to model main conventional and some unconventional methods and associated physical mechanisms of oil recovery. However, it is not the case for high-frequency (HF) electromagnetic heating. New approach is required to extend the reservoir simulator capabilities. The main purpose of our work is to develop adequate numerical tools for evaluation of the technology based on HF heating of oil deposits. In particular, we will show how the code coupling based on COMSOL *Multiphysics* can be useful in doing what dedicated reservoir simulators are not able to do.

Other benefit came from the intrinsic features of the finite-element based multiphysics simulator in the framework of so-called loose coupling. Indeed, the most important model parameters like computational domain dimension and size, numerical grid, FEM order and shape, solver parameters etc. can be chosen according to assumptions of the EM field model without additional limitations associated to reservoir model.

Recently, promising results for 2D and 3D real size models were obtained within a reasonable computational time. COMSOL based code coupling with a reservoir simulator is an important feature in the EM heating estimation as a method of hydrocarbon recovery from natural rocks.

Keywords: electromagnetic field, dielectric heating, heavy oil recovery.

1. Introduction

Development of novel or a significant improvement of known technologies is required to provide an important enhancement of the oil production dynamics. The world-wide need in new energy sources can be alleviated with the heavy and extra-heavy oil-fields in Canada, Venezuela and, probably, in Russia. The variety of methods called generally an electromagnetic heating (EMH) (cf. [1]) opens a way to these fields development.

All these methods have the same energy source but not the same physical mechanism of the energy conversion to heat. While the low-frequency and inductive heating are based on the Joule effect, the high-frequency (or dielectric, 1MHz to1GHz) heating (HFH) results from the polar molecules friction (such as water molecule) which oscillate in applied EM field.

Mathematically speaking, all these effects are described by the system of Maxwell equations with the generalized description of heating power field based on effective electric conductivity of a medium whatever be the applied EM field frequency and underlying physical mechanisms. Common physical nature of phenomena under consideration explains similar features in the EM field distributions. It turned out that the reservoir water electric properties make the methods applicable for a wide range of reservoir conditions. (There is no heat release in a dry medium).

The advantages of high-frequency methods comprise the fact of "remote" heating through a water-free reservoir region around the EM energy source. However, their practical application may be more expensive and requires a separate study.

Despite considerable progress in experimental and pilot testing of the EMH, the mathematical description of the process up to now has been reduced to the simplified (and cumbersome in use except for analytical models) so-called Beer-Lamber-Bouguer law (BLB) [2] (see also [3]). Formally, its application is restricted to short-time preheating under the boiling-point temperature, i.e. without phase transition, or other situations where strong assumptions on fluids distribution are valid. The connate water evaporation and the steam circulation chamber development put definitely limit to the use of the BLB law in numerical models. As the heating power distribution depends mainly on water saturation field around the EM source, the shape of the steam chamber with zero liquid water content and the water distribution just outside it are equally important in simulations. Both factors are coupled, time-dependent and should be modeled numerically. Finally, in 3D case just a simple visual estimation is enough to conclude that the solution for power field may be non-trivial even for relatively simple models (Figure 5).

2. To couple or … to couple

Modern reservoir simulators are capable to model main conventional and some unconventional methods and associated physical mechanisms of oil recovery. However, it is not the case for the HF electromagnetic heating. To work with such a model one has either to develop a new simulator or to couple an existing code to another phenomenon-specific code. We have chosen to work out a code capable to launch and control the data exchange between the reservoir simulator (Stars by CMG [7]) and COMSOL RF Module.

2.1 Simulators coupling facility

The multiphysics simulator (together with its environment) proved to be a good choice as it is well-suited for coupling (by definition) and different physics (and their combinations) are available for simulations. This recently developed and tested in-house code did carry out coupled simulation of the EMH applications for bitumen reservoir.

The code follows a loose explicit coupling algorithm (cf. [4]) which implies that the EM field and the thermal multicomponent flow models are solved sequentially using different solvers. The finite-volume reservoir simulator solves its usual energy and component transport problem while COMSOL provides the instantaneous heating power distribution. Both solutions undergo certain user-defined transformations during data exchange. For example, the interpolation of necessary composition- and temperature-dependent reservoir properties is done using coupling code utilities and the results are stored on the finite element grid. Furthermore, the finite element computations of the heating power density are followed by the spatial integration of the power over each block of the reservoir model grid.

Each simulator works independently and solves separately the system of equations of different type: transient non-linear parabolic or parabolic-elliptic system of multiphase transport and stationary hyperbolic system of EM field equations. It seems now quite natural that they work with different grids using different solvers. Moreover, the computational regions for coupled problems are not obligatory coinciding so special mapping are specified for the common subdomain. Parallel computations and adaptive meshing have been much involved in our computations.

The comparison to known reference solutions, test problems simulation and computation performance estimation, choice of adequate numerical parameters like grid block sizes, coupling frequency etc. has been carried out during this work [3,5].

2.2 The code interface

Technically speaking, the COMSOL environment provides a complete Java interface which is useful to develop a code coupling software using the same programming language. The greatest benefit of such an approach is the ability to modify easily the COMSOL model depending on in-situ reservoir information received from the reservoir simulator. Note that sometimes the application programming interface (API) has to be extended with some additional features necessary for coupling or simply to improve the computational performance. It means that a developer may adapt their programs according to the specific problem they want to solve. For example, several functions have been developed for the coupling code to compute the heating power per cell of the reservoir model grid and to transmit this information to the reservoir simulator at each coupling time step.

3. Physical formulation and parameters

The 3D space is a natural environment for a reservoir simulator study. Challenging the control of three phase (and sometimes more than that) multicomponent energy and mass transfer in real (i.e. heterogeneous) reservoir media which accounts for numerous injection and production wells configuration and their pattern, inevitably requires the use of 3D problem formulations. It is not always feasible, however, to use full 3D formulation for preliminary analysis and case selection. Our work has been started with a single EM-well (equipped with the emitter and production facilities) which can be modeled in a slightly different framework.

2D radial geometry has been used to model the EMH driven bitumen production (Figure 1). The equipment for EM energy injection may be set up inside a vertical well. Separate production well may typically be installed below the EM field emitter because the gravity drainage is the most reliable production mechanism in this case. The principal feature of the geometry is that this single-well pattern makes possible a fast production after relatively short preheating period (see Figures 2,3; production takes place via EM well; black arrows illustrate local oil velocity direction and magnitude). The initial reservoir conditions and geometrical parameters for the cases under consideration are given in Table 1.

The first objective of our current study was the improved modeling of heated zone development which results after relatively short initial time in a steam circulation chamber expansion. In particular, it was demonstrated that not only the total power but also its distribution in the pay zone may be important for efficient oil recovery. Two burden layers at top and bottom was added to compute more precisely the EM field and power distribution, and also the heat losses from reservoir. Mention also that the grid shown in Figures 1 to 3 is that of the CMG simulator; the finite-element adaptive grid can be much finer locally along the steam chamber boundary. Besides the improved description of the EM power distribution (Figure 3), our second purpose is the investigation of production rate and production efficiency dynamics for different geometries, frequencies and power of the EM field.

The study cases for the single-well problem included the EMH process at different power and wave frequency (1 to 60 MHz), then the production period operations (like water injection and production well pressure variations) to slightly optimize the oil recovery. Generally speaking, the choice of an EM well configuration can influence the distribution of the heating power in the reservoir. Sometimes the power field in radial geometry is more close to spherically symmetric case and, at least, is more compact in the vicinity of the emitter in this case.

The recovery by pure conductive heating provides a physically feasible reference to the considered EMH cases. It was done previously using the same geometry with heating over the whole thickness of pay zone [6].

4. EMH simulation results and discussion

The coupled COMSOL/CMG simulation results for the problem of bitumen recovery driven by the EM heating are presented in some details in this section. Note that the bitumen is immobile at reservoir conditions and only the heating will allow to reduce its viscosity and therefore to produce it (Figure 4). The factors influencing the production efficiency, the advantages of applied method but also possible improvements of the code computational performance, are presented and discussed.

4.1 Oil recovery and its energy efficiency

The heat transfer by conduction is crucially important for any EMH based process. The conduction diminishes the temperature difference inside the reservoir and may also underlie a thermal recovery process where energy is supplied to reservoir without injected fluid. This may create a strong short-time power density of heating.

Nevertheless the EM heating is expected to be more efficient during years of production period due to both deeper instantaneous energy penetration (and therefore more efficient heating) and the effect of heating power sweep from liquid water free part of the reservoir (like the steam circulation chamber) which provides “remote” heating of the cold oil.

The typical physical fields during EMH are strongly related to the frequency (cf. absorption length, ℓ, equation A-5a). Relatively short absorption length causes fast development of the steam chamber resulting in oil accumulation and production by gravity drainage. The oil saturates almost entirely a certain part of the heated region which is a positive factor for its recovery efficiency.

At greater ℓ the preheated bitumen volume increases; at higher emitted EM energy the steam chamber development becomes faster. Both tendencies have been observed and one may conclude that more homogeneous heating and growing total heating energy result in more efficient production.

4.2 Radiation heating power computations

An accurate radiation heating power estimation is certainly the most important point in the coupling method developed. Even if the computation seems easy, several technical elements make the task much more complex. Let's forget for the moment about natural medium heterogeneity, quasi-singular geometry of the power source, strong EM field attenuation, frontal-like electrical properties field. The main difficulty turned out to be the "interpolation" of the heating power integral between the finite element and the finite volume mesh. To deal with this problem an assumption is made in the COMSOL model conception.

In the part of the COMSOL model in which the estimation is required, a mesh element may not belong to more than one finite volume grid element. So the information transfer from COMSOL to the reservoir simulator is natural. Unfortunately, this assumption limits the simulation to a fixed mesh at the beginning and failed to give us the opportunity to use the adaptive mesh refinement available in the COMSOL interface. To overcome this problem, mesh information between each simulator should be exchanged at each time step and COMSOL model should be adapted automatically.

The advantages of such an improvement will be to follow with accuracy the evolution of the liquid water free zone in the reservoir and so, the distribution of the heating power as illustrated by Figure 3.

5. Conclusions

● In-house code launching and controlling two powerful simulators was developed using COMSOL environment and proved its operational applicability to 2D and 3D oil recovery problems;

● 3D large-scale problem solution by RF Module for radiation heating in variably saturated natural porous medium possessing intrinsic heterogeneity underlay the numerical analysis of heavy oil production scenarios;

● the code demonstrated the advantages of loose coupling and successfully used the capabilities of both simulators.

6. References

1. Ritchey H.W., Radiation heating, *Patent US2757738* (1956)
2. Bouguer P., *Essai d'optique sur la gradation de la lumière*. Claude Jombert, Paris (1729)
3. Fanchi J.R., Feasibility of Near-Wellbore Heating by Electromagnetic Irradiation, *SPE Advanced Technology Series*, **1**, 161-169 (1993)
4. Weick K., *Making Sense of the Organization*, 483 pp., Blackwell Publishing Ltd. (2001)
5. Cambon S., Bogdanov I.I., Electromagnetic field computations for saturated porous media, *European COMSOL Conference*, 10-12 October, Milan, Italy, 2012
6. Bogdanov I., Kamp A., Torres J.A., Corre B., Comparative Analysis of Electromagnetic Methods for Heavy Oil Recovery, *SPE 150550-PP*, paper presented at the SPE Heavy Oil Conference & Exibition, Kuwait City, Kuwait, 12-14 December, 2011
7. CMG STARS User's guide, 2010

7. Acknowledgements

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8. Appendix

As it has been stated above, COMSOL computes instantaneous heating power distribution. To do this the coupling code performs certain data transformations during exchange with the CMG simulator. This includes, for example, possible interpolation of necessary reservoir physical properties which is done for subsequent use in the bulk medium electrical properties calculations according to the equations A-2, A-3, A-4. Adversely, the power integration (cf. equation A-1) is performed over CMG grid block and the results are outputted as a table. Below are the equations used in both simulators.

8.1 EM heating power density

The coupling term between the EM field and multiphase flow equations is the heating source which generally reads as

$$J = \mathrm{Re}\left(\sigma |E|^2\right) \qquad \text{(A-1)}$$

Here J is the heating power density; σ the effective bulk electrical conductivity and E the (complex) electric field. The calculation of the effective electrical conductivity of reservoir is an important point in this study since it depends generally on (multiphase) fluid composition, frequency, temperature etc. This is a complex value taking into account conductive and dielectric phenomena and containing typically two terms

$$\sigma = \sigma_B + i\omega\varepsilon_0\varepsilon_r \ , \qquad \text{(A-2)}$$

where σ_B is the bulk reservoir conductivity given conventionally by Archie's law (see below), ω angular EM wave frequency, ε_0 electric constant (void space electrical permittivity), ε_r bulk relative electric permittivity (for which linear mixing law has been chosen). The latter means that both components of complex permittivity ε_r ,

$$\varepsilon_r = \varepsilon_r' - i\varepsilon_r'' \ , \qquad \text{(A-3)}$$

are proportional to volume fractions of fluids in pores (i.e. fluid saturations). Here ε_r**'**, ε_r**"** are real and imaginary part of reservoir relative permittivity, $i=(-1)^{1/2}$. The standard formulation of Archie's law (without temperature dependency factor) is used in current work which reads as

$$\sigma_B = \beta\sigma_w\phi^m S_w^n \ . \qquad \text{(A-4)}$$

Here σ_w is the liquid water electrical conductivity at reference conditions, ϕ porosity, S_w water saturation, β, m and n the constant parameters (β being reciprocal to tortuosity factor).

There is at least one more physical parameter which is important during EMH and should be specified here. It is so-called energy absorption length which characterizes the heating power attenuation (cf. Fanchi, 1993) and may be written as

$$l = \left\{ \sqrt{2}k_0 \cdot \left[\left(\varepsilon_r'^2 + \left(\varepsilon_r'' + \frac{\sigma_B}{\omega\varepsilon_0} \right)^2 \right)^{1/2} - 1 \right]^{1/2} \right\}^{-1} \qquad \text{(A-5a)}$$

This gives for non-conducting medium (at $|\varepsilon_r|>>1$)

$$l \approx \left(\sqrt{2}k_e\right)^{-1} \qquad \text{(A-5b)}$$

Here $k_e=k_0\varepsilon_r^{1/2}$, $k_0=\omega/c$ is the EM wave number and c speed of light, both taken in empty space.

So the heating power J is finally a solution-dependent variable and the strong physical coupling occurs between electrical and thermal flow phenomena.

8.2 EM field model

Harmonic EM field formulation has been used for computation of power density term given by (A1). The electric field was determined either from resulting equation for the harmonic field which can be written as

$$\nabla\times\nabla\times\mathbf{E} + k^2\mathbf{E} = 0 \qquad \text{(A-6)}$$

or provided magnetic field problem solution, it can be determined directly from Faraday's law (the equation written for harmonic field)

$$\nabla\times\mathbf{E} = i\omega\ \mathbf{B} \qquad \text{(A-7).}$$

Here k is the (complex) wave number for the EM field in reservoir where the propagation velocity depends on medium electromagnetic properties (such as relative permittivity ε_r and relative magnetic permeability μ_r), B is magnetic flux density vector. The model accounts for variable physical properties of reservoir including a particular case of a composite-like medium with sharp properties variation like it may often happen due to the appearance and expansion of the steam circulation chamber.

Note finally that the linear dimensionless equation A-6 for $\hat{E}(\chi,\psi,\xi)$ where $\hat{E}=E/E_0$, $(\chi,\psi,\xi)=(k_0x,k_0y,k_0z)$, shows that dimensionless electric field $\hat{E}$ depends only on electric properties distribution in reservoir, $\varepsilon_r(k_0x,k_0y,k_0z)$.

Table 1: RESERVOIR CONDITIONS AND MODEL PARAMETERS

External radius	70	m
Reservoir thickness	20	m
Porosity	30	p.u.
Permeability, vertical/horizontal	5/1	D
Rock volumetric heat capacity	$1.94 \cdot 10^6$	$J/m^3/°C$
Burdens volumetric heat capacity	$2.01 \cdot 10^6$	$J/m^3/°C$
Burdens thermal conductivity	$2.22 \cdot 10^5$	J/m/d
Oil initial viscosity	560	Pa·s
Injection pressure	1.16	MPa
Initial reservoir pressure	1	MPa
Initial reservoir temperature	15	°C
Initial water saturation	0.2	undim.
Initial bulk relative permittivity, imaginary part	0.48	undim.
Initial bulk relative permittivity, real part	7.38	undim.

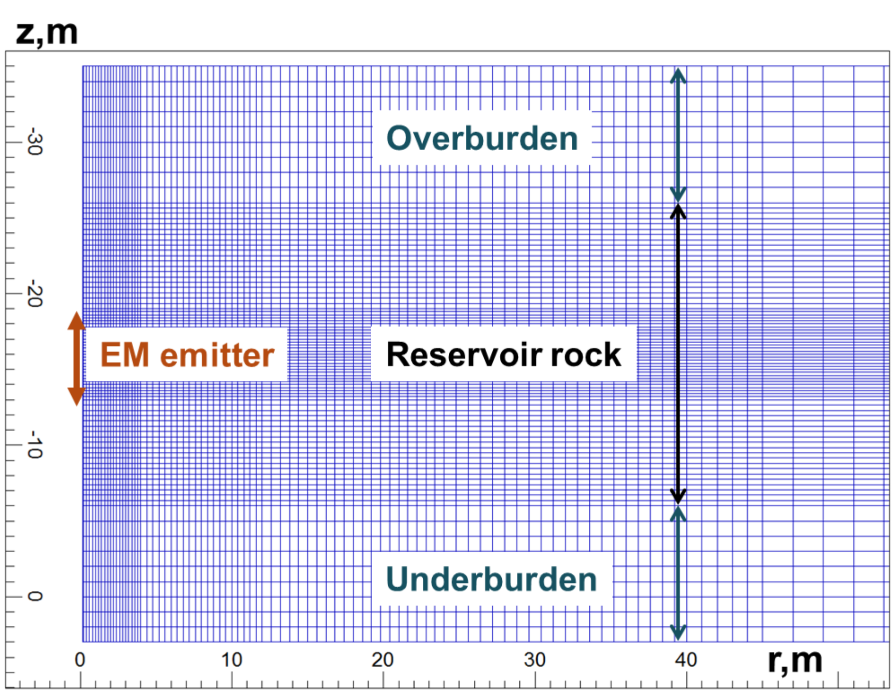

Figure 1. Geometry and the reservoir simulator grid.

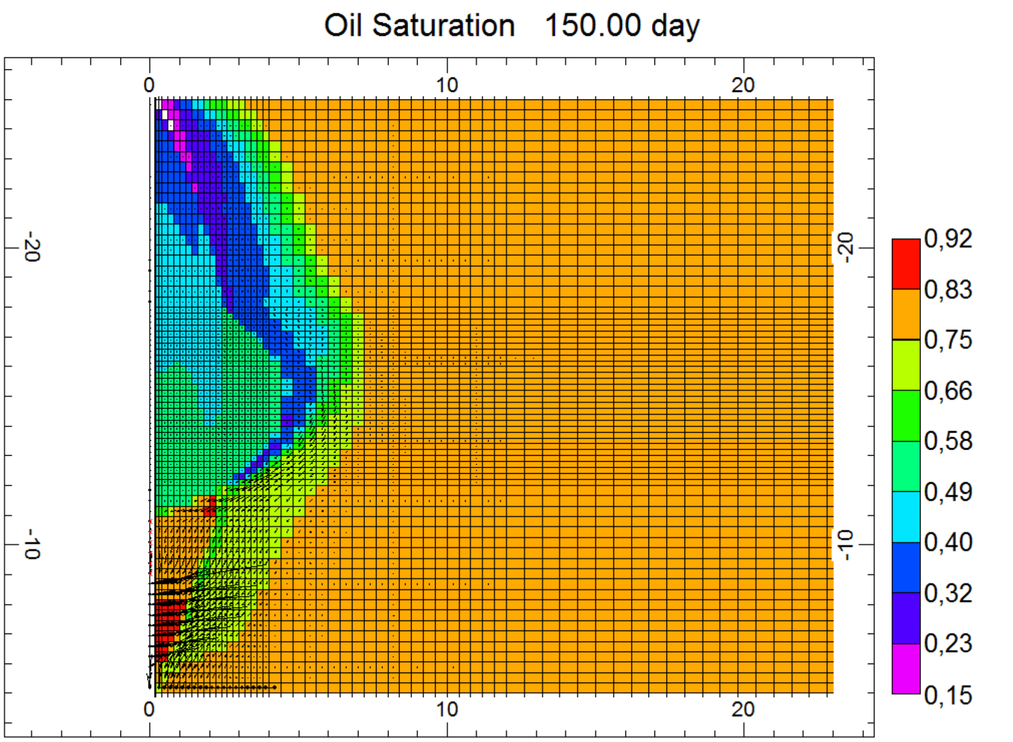

Figure 2. Oil saturation field after 150 days of the process.

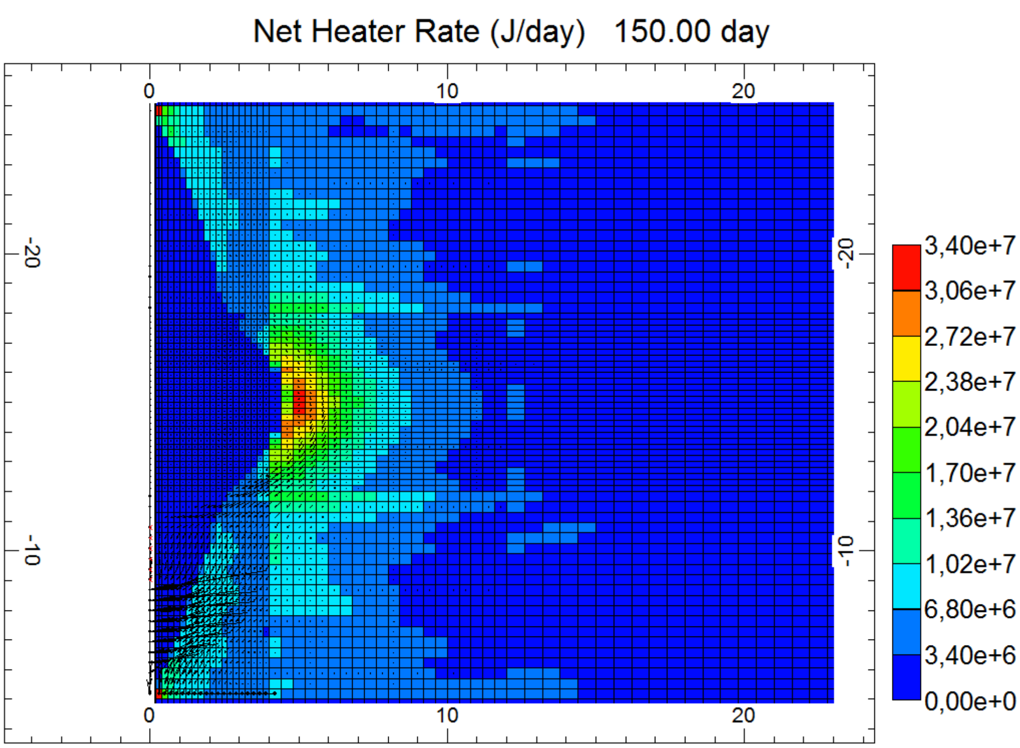

Figure 3. EM power field after 150 days of the process.

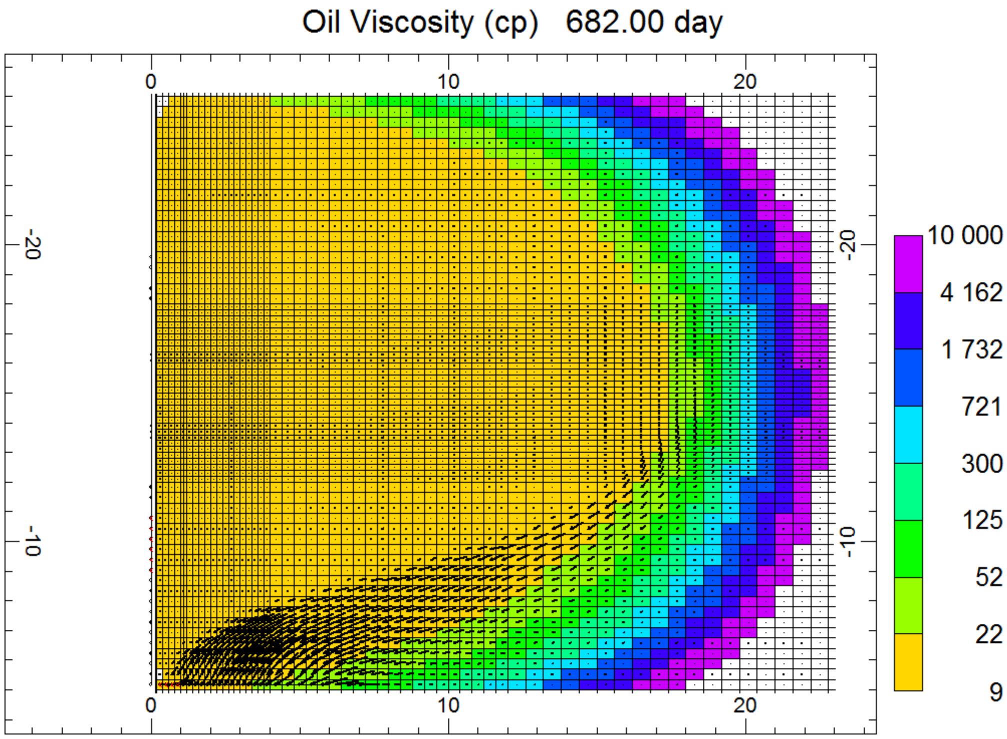

Figure 4. Oil viscosity field and flow lines towards production well; initial oil viscosity is 10^6 cP

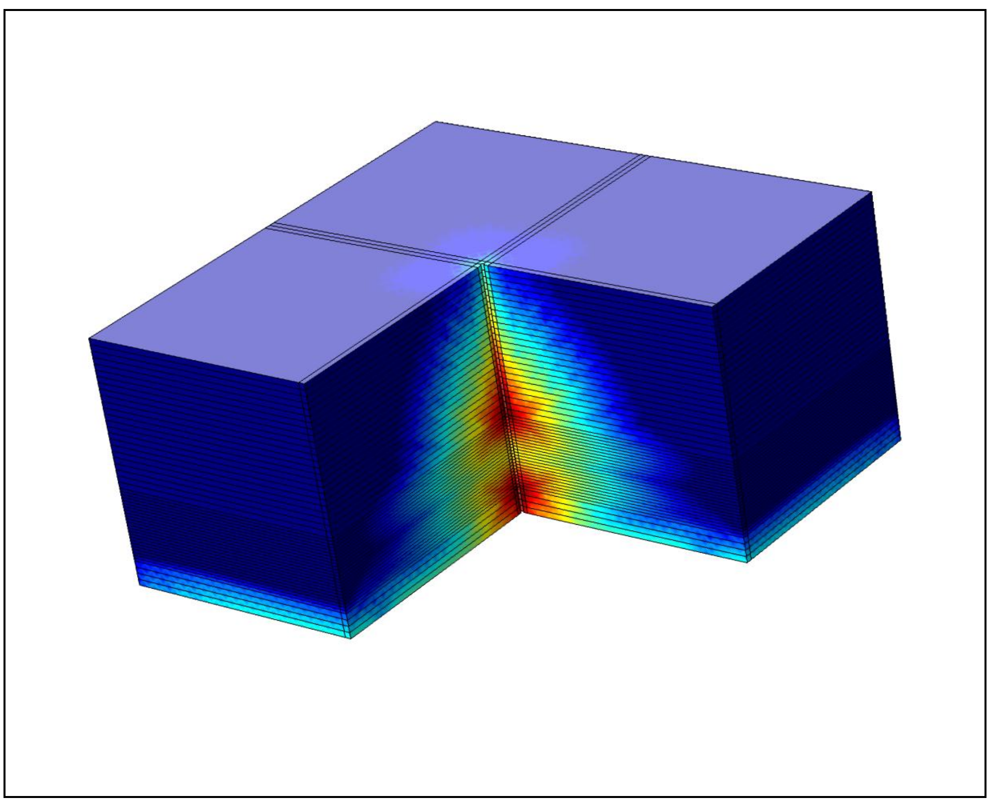

Figure 5. Example of 3D EM power field in the reservoir volume induced by the emitter in the center.