Modeling of EM Assisted Oil Recovery

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***Abstract* – An algorithm for rigorous analysis of electromagnetic (EM) heating of heavy oil reservoirs is presented in the paper. The algorithm combines an FDTD-based EM solver with a reservoir simulator, utilizing the fact that the two simulators operate at completely different time scales. The two simulators also utilize different grids. Special attention needs to be taken when interpolating the values between the two grids to avoid occurrence of non-physical effects. An example of a vertical 50-m long dipole antenna heating a heavy oil reservoir in northern Alberta, Canada is presented.**

1 INTRODUCTION

The technology for downhole heating of oil reservoirs using radio frequency (RF) energy has been considered since the 80's [1-3]. The underlying scientific premise was sound and rather simple and was confirmed by basic experiments. However available modeling/prediction tools were grossly inadequate, practical implementation of technology difficult and expensive, and appreciation for the complexity of the problem lacking. All this lead to lack of commercial success and technology remained in its infancy. However, diminishing conventional oil reservoirs and high oil prices renewed interest in this alternative exploitation technology. Recent, significant advancements and use of sophisticated numerical tools have provided a much deeper understanding of the underlying complex electrical and reservoir engineering issues involved in downhole RF heating oil recovery. Consequently, this technology is now much closer to be commercially viable. It is envisaged to be used as either complementary or replacement to traditional steam based methods, and it offers significant advantages over conventional thermal processes, mainly in its energy and environmental footprint.

The basic principle of this technology is to deploy an antenna or applicator downhole and radiate an RF field into an oil-bearing formation such that the temperature of the heavy oil is raised in the required volume, viscosity of oil lowered and, hence, production enabled. The process is typically indirect: water present in the reservoir is heated and that heat is transmitted to the heavy oil, reducing the oil viscosity and enabling commercial production. The challenge in modeling and forecasting the behavior of a reservoir under this process is that two mature but very different simulation technologies need to be closely integrated and run simultaneously. This is to be contrasted with the available “multi-physics” solvers. The latter were developed as general purpose software, and lack the specialization and sophistication of a reservoir simulator like CMG’s STARS or maturity and sophistication of modern electromagnetic (EM) simulators.

In the presentation we will describe some challenges related to integration of advanced electromagnetic codes with reservoir simulators, and about necessary numerical technology that needed to be developed, particularly as it relates to the multi-physics, translation of meshes, as well as petro-physical and EM material parameters, as well as challenges with calculation of electromagnetic dissipation in the vicinity of the antennas.

The numerical methods will be illustrated with computations performed using AxHeat package (Acceleware) that utilizes reservoir code STARS (CMG). The code allows for realistic prediction of formation behaviour in time, including losses (both EM and thermal) in feeding systems, cooling fluids and oil production effects on the reservoir dynamics.

2 RF HEATING PROCESS

An RF antenna inside an oil well is used to radiate the EM energy into the oil-bearing formation. A typical antenna would be a dipole or a loop; however, other types of antennas and/or arrays are also being considered. In most applications, the frequencies used are between 10 kHz and several 100s of MHz. At higher frequencies, the penetration of the EM field into the reservoir is simply not far enough.

Due to the initial presence of brine and certain minerals, the formation is electrically lossy with the conductivity in the range between 10^{-3} and 1 S/m [3]. Therefore, the propagating EM wave will heat the formation. Since the field is strongest in the area around the well, this area will be heated first. When the temperature in this zone reaches the water boiling point, the water converts into the steam generating the dryout zone. The electrical conductivity of the dryout zone decreases significantly, reducing the EM power dissipation in that region. Therefore, the heating in the dryout zone stops and moves on to the adjacent colder area.

The EM field pattern is governed by the frequency, antenna type and size, as well as the EM properties of the formation and the well components, such as liquids inside the well and the casing. During the heating process, the heat created by the dissipation of the EM field causes changes of the formation's petrophysical parameters, such as the water saturation, temperature and pressure [1-3]. This, in turn, changes the EM properties of the

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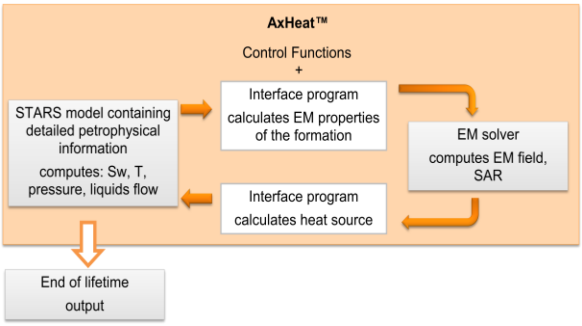

Fig. 1 Flow diagram of the RF heating simulation software.

formation and the well materials, which modifies the EM field pattern. Therefore, an accurate simulation of the RF heating process requires a combined work of EM, thermal and reservoir simulators.

3 THEORETICAL MODEL

The EM simulator calculates the EM field distribution in the reservoir, using the antenna geometry, well and the formation features, as well as the EM properties of the materials involved. The simulator can also calculate the losses occurring inside the feeding waveguide and the antenna itself, due to the lossy nature of the metals used in their construction. The EM field distribution is obtained by solving Maxwell's equations in the discretized computational domain. For completeness, time-domain Maxwell's curl equations are given below [4]

$$\nabla\times\vec{H}=\varepsilon_0\varepsilon_r\frac{\partial\vec{E}}{\partial t}+\sigma\vec{E}$$

$$\nabla\times\vec{E}=-\mu_0\mu_r\frac{\partial\vec{H}}{\partial t}+\sigma^*\vec{H} \qquad (1)$$

where $\vec{E}$ and $\vec{H}$ are the electric and magnetic field vectors, μ_0 and ε_0 are the permeability and permittivity of vacuum, μ_r and ε_r are the relative permeability and permittivity of the materials used, while σ and σ^* are the electrical and magnetic conductivities.

The reservoir simulator calculates the temporal temperature evolution, fluids flow, and the change of reservoir conditions. The temperature evolution is calculated using Pennes heat equation [5]:

$$\rho c\frac{\partial T}{\partial t}+\rho_f c_f\vec{v}_f\cdot\vec{\nabla}T=\nabla\cdot\left(k\vec{\nabla}T\right)+\dot{Q} \qquad (2)$$

where $\rho, c,$ and k are the density, specific heat capacity and thermal conductivity of the medium, ρ_f, c_f, and v_f are the density, specific heat capacity and superficial velocity of the fluid phase. $\dot{Q}$ is the heat generation rate per unit volume. In the RF heating process, the heat generation rate is equal to the EM power density [5], i.e

$$\dot{Q}=P=\sigma|E|^2 \qquad (3)$$

The fluids flow in the formation is described by the mass conservation equation combined with the momentum equation (Darcy's law) for each fluid phase *i* (water, oil, gas), written as [6]:

$$-\nabla\cdot\frac{\vec{v}_i}{B_i}-\frac{q_i}{\rho}=\frac{\partial}{\partial t}\left(\phi\frac{S_i}{B_i}\right) \qquad (4)$$

where v is velocity, B is the formation volume factor, q is the production/injection, ρ is the density, ϕ is the porosity and S is the saturation. Generalized Darcy's law, included in the velocity variable (v_i) is expressed as [6]:

$$V_i=-\frac{K_i}{\mu_i}\frac{\partial\Phi}{\partial j} \qquad (5)$$

where K_i is the permeability, μ_i viscosity, Φ is the fluid potential, i is the fluid phase, and j denotes direction (x, y, z).

3 NUMERICAL MODELING

A rigorous simulation of the RF heating process would require simultaneous solution of equations (1)-(5). However, such approach would be very expensive. To simplify the solution, we can recognize that the time-scales involved in electromagnetic and petrophysical processes are vastly different. While the EM field is established within nanoseconds, the fluid/thermal movements take hours, days and years. This means that a reasonable accuracy is maintained while system 1, comprising equations (1) and describing the EM process, and system 2, comprising equations (2)-(5) and describing the petrophysical process are solved separately. The overall, RF heating process is simulated by iterating between the software solving system 1 (EM solver) and the software solving system 2 (reservoir solver). Because of the vastly different time-scales at which the two solvers work, the EM solver can consider the reservoir conditions as static at its time scale, while the reservoir solver, at its time scale, can consider EM field as changing instantaneously.

In this project, an algorithm which closely integrates an FDTD-based EM solver with CMG's STARS reservoir simulator is developed. For faster simulations, the FDTD code is designed for parallel execution on CPU and/or GPU processors. The algorithm is named AxHeat and its flow diagram is shown in Fig. 1.

3.1 Algorithm

The total simulation time is divided into user-defined timesteps. In each timestep, the reservoir simulator, STARS, calculates the flow of the fluids in the reservoir, temperature distribution and change of the reservoir conditions. The obtained temperature distribution and brine concentration are used by AxHeat to calculate the EM properties of the formation. The relationship between the temperature, water saturation and the EM properties can be obtained theoretically [3] or through measurements [1-2]. The calculated EM properties are fed to the EM solver, which then calculates the new field distribution and the RF power absorbed by the formation. This information is used by AxHeat to calculate the heat generation rate, using (3). Finally, the heat generation rate is fed to STARS which continues with the reservoir simulation during the next timestep. The simulation continues until the end of the total time period required by the user. As output, the reservoir properties such as temperature distribution, water/oil saturation, pressure and oil production are obtained.

3.2 Integration challenges

One of the most important numerical challenges in the implementation of the algorithm is the interpolation of the reservoir parameters and the EM field values from one grid to another. The discretization grids used by the two solvers (EM and reservoir) are significantly different because they are used to describe different problems. While STARS grid contains cells which can be 1 – 100 meter long in some directions, the EM grid is generally much finer, especially the part discretizing the antenna and well. The two grids overlap, but are generally not aligned.

The reservoir parameters, such as water saturation and temperature are calculated by STARS on its grid. Therefore, the formation EM parameters are initially calculated on the same grid as well. These parameters are then mapped to the FDTD grid using weighted averaging.

Going backwards is more complex. The EM power is calculated on the FDTD grid. However, simple weighted averaging of this power back to the STARS grid may cause artificial overheating of certain areas, such as dryout zones. This would happen because of the FDTD cells overlapping one STARS cell representing a dryout region and one STARS cell representing a wet region. If the power of these FDTD cells is simply split between the two STARS cells, the STARS cell would receive more power than it should, which would cause overheating. Therefore, the proper power splitting needs to take into account the electrical parameters of each STARS cell. The interpolation challenges become even more pronounced when non-structured grids are used by the reservoir simulator.

Another detail which needs to be considered in the simulation of the RF heating process is the EM radiation absorbed by the boundaries of the computational domain. To achieve accurate results, this power needs to be calculated and included in the power balance equation.

Finally, losses in the antenna and the feeding transmission line (coaxial cable) need to be calculated and considered in the simulation. These losses can be significant, especially when the RF power is in the range between 100 kW and several MW. These losses will cause significant heating of the antenna, feeding line and the well materials. Therefore, proper cooling mechanism needs to be established.

4 RESULTS

AxHeat algorithm is used to simulate an RF heating process in a typical oil sand reservoir in northern Alberta, Canada. A 50-m long dipole antenna is inserted in a well with an 20 cm outer diameter. Inside the well, a hydrocarbon-based liquid is used for cooling of the antenna and well materials. The well casing is made of fiberglass.

Initial temperature in the reservoir is approximately 15^o C. At this temperature, the viscosity of the heavy oil is in the order of millions of cp. With this viscosity, the oil is practically solid and cannot be moved or produced. To be able to produce the oil, its viscosity needs to be lower below 100 cp, i.e. the reservoir temperature needs to be raised to about 200^o C.

To achieve such heating, 150 kW of RF power is supplied to the antenna via a 5-inch OD coaxial cable. A static heating process (no oil produced) is maintained for 2 years. The temperature distribution in the reservoir after 654 days is shown in Fig. 2. A zone around the antenna with approximately 10-m radius has been heated to close to 200^o C. This temperature corresponds to the steam saturation temperature at the given pressure in the reservoir (between 800 kPa and 1000 kPa).

The spreading of the heating pattern with time is illustrated in Fig. 3 and 4, showing the net heat generation rate (proportional to the absorbed power) at the initial moment and after 654 days, respectively. Initially, the heating is strongest in the area immediately around the well. However, after 654 days, dryout (white) zones have been formed and heating is moved on to the adjacent colder areas.

5 CONCLUSION

An algorithm for rigorous modeling of the RF heating process is presented. The algorithm combines an EM simulator with a reservoir simulator to achieve accurate simulation of the heating process. The two simulators work in vastly different time-scales and utilize discretization grids of different

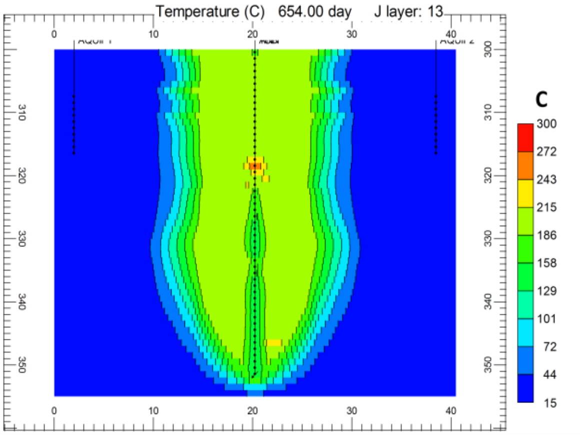

Fig. 2 Temperature distribution around the antenna well after 654 days of continuous RF heating.

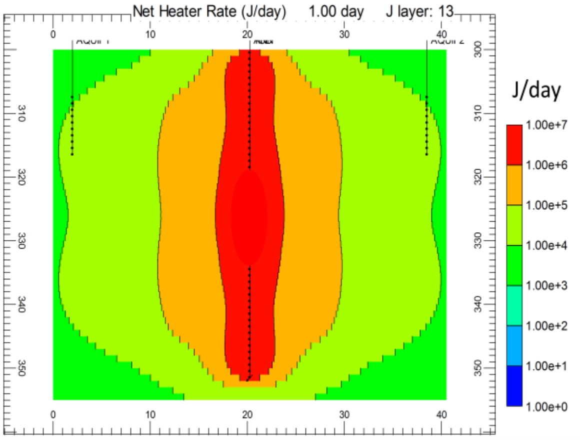

Fig. 3 Heat generation rate in the area around the antenna well at the beginning of the heating process.

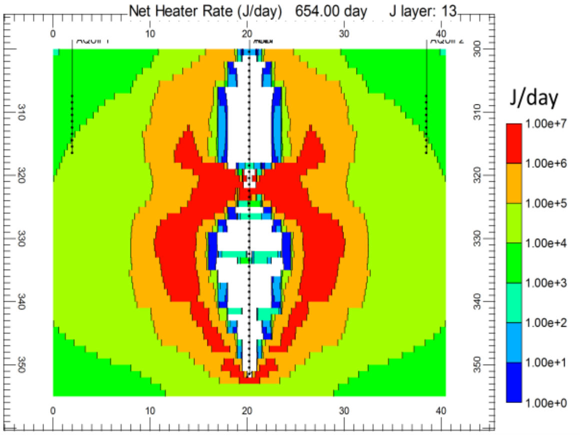

Fig. 4 Heat generation rate in the area around the antenna after 654 days of RF heating.

sizes. Special attention needs to be taken when interpolating values from one grid to another to avoid artificial overheating. Additionally, the power leaked through the absorbing boundaries and dissipated in the antenna and well materials needs to be taken into account for accurate results. Finally, an example of a 50-m long dipole antenna inserted in a vertical well in a homogeneous formation and heating the formation for 20 months is presented.

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