Parametric Study of Heavy Oil Recovery by Electromagnetic Heating

M.Y. Liu[1], and G. Zhao[*2]
[1]University of Regina, [2]University of Regina
*Faculty of Engineering and Applied Science, Regina, SK, Canada, S4S 0A2; email: gang.zhao@uregina.ca

Abstract: Downhole electrical heating has proven to be an effective way of lowering the oil viscosity by raising the temperature in the formation. The application of low-frequency electrical resistance heating (ERH) limits the heating rate as well as the production rate. Electromagnetic heating (EMH) can be used instead. This study presents an oil-gas two-phase linear flow EMH model by COMSOL. The model uses the variation in temperature to update the EM absorption coefficient. Special attention is focused on reservoirs with characteristics for which steam injection is not feasible such as low permeability, thin-zone, and extra-heavy oil reservoirs. Comparisons showed that cumulative oil production obtained by EM heating are better than what is achieved by a similar enhanced oil recovery technique called single well steam assisted gravity drainage (SW-SAGD) process simulated with STARS for reservoirs with the above mentioned characteristics.

Keywords: heating, viscosity, reservoir, simulation, temperature

1. Introduction

In the case of reservoir heating there is a wide range of available frequencies in the electrical spectrum that can be used in diverse heating schemes. In ERH, also known as low frequency heating, the heat source is assumed to be inside the production well using a hot pipe, a constant temperature is assumed at the boundary of the well. In EMH, a uniform heat distributed through the entire volume is assumed, which is also called volumetric heating. This method can uniformly heat up the media with approximately a constant rate until the evaporation temperature of water is reached. The heating rate drops as the media dries up but uniform temperatures of more than 250°C can be reached with this method.

Heating with frequencies less than 300 kHz is also known as ERH (Maggard and Wattenbarger, 1991). In this thermal recovery method, electrical current passes through the formation and heats by Joule effect (de Oliveira et al. 2009). The heating occurs when the induced electric current passes through a resistive element under a voltage gradient. The analysis of low frequency heating can be carried out through a circuital approach based on the application of Kirchhoff’s laws. The parameters used are voltages, currents, resistances, capacitances and inductances. Low frequency heating causes a smaller temperature rise near the wellbore zone than high frequency heating does. This condition imposes a restriction on the production response that can be obtained with ERH. In general, radiation with frequencies within a range of 10 to 100 MHz are referred to as radio frequencies (RF), and in the range of 300 MHz to 300 GHz as microwave (MW), and corresponding wavelengths from 1 to 0.001 m. According to laboratory measurements, oil-bearing sands can absorb RF or MW energy and reach very high temperatures (300 to 400 C) very rapidly as does steam injection. The dielectric properties of the soil not only depend on temperature but also on the water content. The analysis of high frequency heating is described by Maxwell’s equations with material properties represented by permittivity, magnetic permeability, and electrical conductivity. In this range the process is defined as electromagnetic heating (EM heating).

It also shows the significant advantage of the electrical heating over other thermal recovery techniques under certain constraints and big challenges in the real field. Steam injection is currently considered the most effective method for heavy oil production. However, there are certain situations where it may not work very well. These could be, for example:

1. Deep formations, where heat losses in the wellbore are significant and the quality of steam reaching the formation is very low.
2. Thin pay-zones, where heat losses to adjacent (non oil-bearing) formations may be significant.
3. Situations where generating and injecting steam may be environmentally unacceptable or commercially uneconomical (in space limited offshore platforms).
4. Low permeability formations, where steam injection might be difficult.

5. Heterogeneous reservoirs, where high permeability streaks or fractures may cause early injected fluid breakthrough and reduce sweep.

The outline of this paper is as follows. Further discussion on two-phase linear flow in petroleum reservoirs is provided in the following section 2, where in particular the mathematical formulation of the flow and heating problems are given. Basic model description is given in section 3, where also some details concerning two simulators' implementation are explained. Numerical results are finally provided in section 4. The good performance of the EMH is shown by numerical comparisons to SW-SAGD, a popular test case scenario in heavy oil reservoir simulation with two leading commercial simulators, COMSOL and STARS.

2. Governing Equations

2.1 Oil-Gas Two-Phase Linear Flow EMH Model

Linear flow is common for laboratory evaluation of EM heating, while radial and spherically flow occur within a reservoir. However, linear flow can be observed even during the early time period when the horizontal well or fracture exist. Two continuity equations can be derived for each of the wetting and non-wetting phases:

$$\frac{\partial(\rho_w s_w)}{\partial t} + \nabla \bullet [-\rho_w \frac{k_{rw} k_{abs}}{\mu_w} \nabla(p_w + \rho_w g D)] = 0 \quad (1)$$

$$\frac{\partial(\rho_{nw} s_{nw})}{\partial t} + \nabla \bullet [-\rho_{nw} \frac{k_{rnw} k_{abs}}{\mu_{nw}} \nabla(p_{nw} + \rho_{nw} g D)] = 0 \quad (2)$$

Where k_{abs} is the absolute permeability, D is the elevation direction, k is relative permeability, s is saturation, μ is dynamic viscosity, p is pressure, ρ is density, and subscripts w and nw represent wetting and non-wetting phase respectively.

The capillary capacity of the wetting phase in contact with the non-wetting phase is defined as the slope of the capillary head curve versus the wetting phase saturation:

$$C_w = \frac{\partial s_w}{\partial h_c} = \rho_{H_2O} g \frac{\partial s_w}{\partial p_c} \quad (3)$$

where the capillary pressure is defined as $p_c = p_{nw} - p_w$. It is assumed that the wetting phase (bitumen) is incompressible but the non-wetting phase (i.e. air or gas) is compressible. According to the ideal gas law, variation in the non-wetting phase pressure and temperature has a direct effect on the density of this phase as follows:

$$\rho_{nw} = \frac{p_{nw}}{p_o} \frac{T_0}{T} \rho_o \quad (4)$$

where the subscript o represents the non-wetting phase characteristics at ambient condition. By substituting all the above assumptions into Equation 1 and 2, and by using the chain rule, the following equations can be derived:

$$\frac{C_w}{\rho_{H_2O} g} (\frac{\partial p_{nw}}{\partial t} - \frac{\partial p_w}{\partial t}) + \nabla \bullet [-\frac{k_{rw} k_{abs}}{\mu_w} \nabla(p_w + \rho_w g D)] = 0 \quad (5)$$

$$\rho_{nw} \frac{C_w}{\rho_{H_2O} g} (\frac{\partial p_w}{\partial t} - \frac{\partial p_{nw}}{\partial t}) + s_{nw} \frac{\rho_o T_0}{p_o T} \frac{\partial p_{nw}}{\partial t} - s_{nw} \frac{\rho_o T_0}{p_o T} \frac{p_{nw}}{T^2} \frac{\partial T}{\partial t} + \nabla \bullet [-\rho_{nw} \frac{k_{rnw} k_{abs}}{\mu_{nw}} \nabla(p_{nw} + \rho_{nw} g D)] = 0 \quad (6)$$

An overall energy balance, including conduction and heat source terms, is defined as follows:

$$\rho_m C_{p,m} \frac{\partial T}{\partial t} + \nabla \bullet (-k_m \nabla T) = Q_h \quad (7)$$

where k is heat conductivity, $C_{p,m}$ represents heat capacity, Q_h is rate of heat generation due to EMH, and subscript m represents the reservoir media.

2.2 Initial and Boundary Conditions

For Equations 3 and 4 the following initial conditions were assigned:

$$at\ t = 0 \quad p_w = \rho_w g(thick - D) - p_{c,\text{int}}$$

$$at\ t = 0 \quad p_{nw} = \rho_w g(thick - D)$$

Uniformly initial temperature is assumed for the energy balance equation. In addition, a no flow boundary condition was imposed at the top and bottom of the reservoir to solve for pressure, and heat flux continuity was assumed at the same boundaries to solve for temperature. The latter condition introduces the effect of vertical heat loss through the boundaries.

3. Model Description

Since EMH is considered as a viscosity reduction process for heavy and extra-heavy oil recovery, it is pertinent to compare the energy efficiency of this process with steam injection. Among the different well-known processes that involve the injection of steam into the reservoir, single well SAGD was chosen primarily because of the use of a single horizontal well scheme for the process.

The STARS simulator was used for the SW-SAGD case, and one of the STARS examples *sthrw009.dat* released with Version 98.01 (1998) was chosen for the comparison study in this work. It represents a typical Alberta reservoir. Fig. 1 displays cross-sections along the length of the well in STARS. The grid system is Cartesian with local grid refinement immediately around the 800 m long well. We assume that wells will be developed in multiple patterns and thus all boundaries are no flux. The single horizontal well is modeled using two individual discretized wellbores, each equal in length and placed directly end to end. Fig. 2 shows the grid system used in COMSOL, and the well has been set in the middle to maximize the EMH effect. Table 1 lists the exact dimensions of the reservoir model, grid-block information, and reservoir properties applied in both simulators. Initially, the average reservoir pressure is 2,654 kPa, the pressure distribution is hydrostatic, and the reservoir temperature is 20 °C. Reservoir properties are also given in Table 2. Fig. 3 displays graphically the gas-liquid relative permeability curve. The relation of oil viscosity and temperature is displayed in Fig. 4. Steam injection rate was 150m^3/day of 90% quality. Instead of injecting steam and producing oil from the beginning as continued SAGD process, cyclic steam stimulation was applied to pre-heat the reservoir due to the lack mobility of heavy oil inside the reservoir and increase the productivity. No heat loss along the wellbore was included. Comparisons of production improvement were made based on the premise that the same total amount of energy (650MMBtu) was input to the reservoir either in the form of the EM energy or as injected steam over a 3 years period.

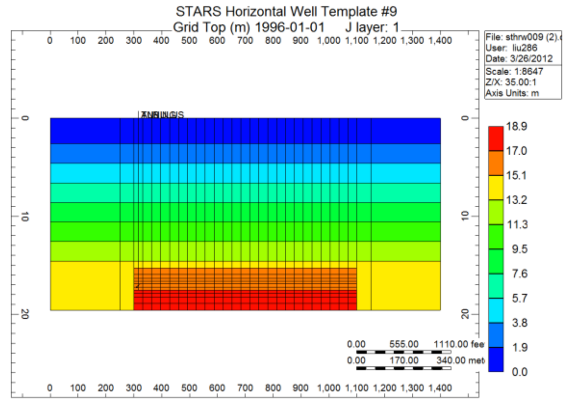


Fig. 1 Grid system for 2-D SW-SAGD (in STARS)

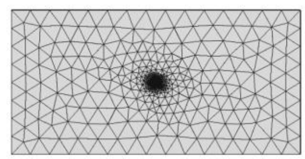


Fig. 2 Grid system for 2-D two phases EMH (in COMSOL)

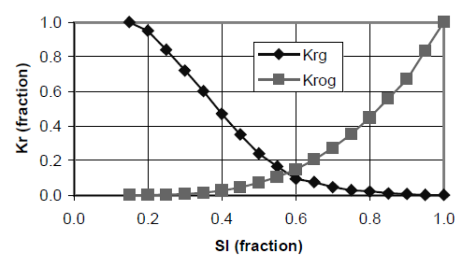


Fig. 3 Gas-Liquid relative permeability curve

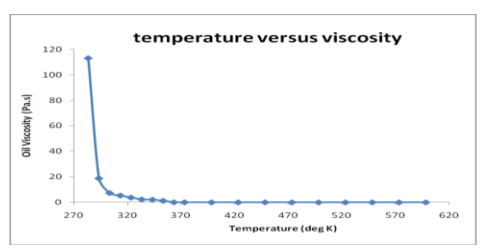


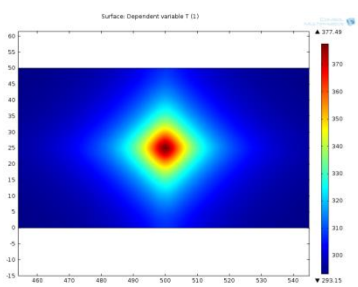
Fig. 4 Oil viscosity /temperature relationship

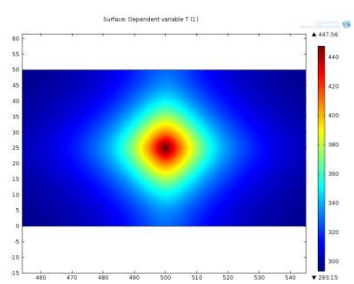
Table 1 2D oil-gas two-phase model description

3D Cartesian system Hybrid grid surrounding well	
x-dimension(m) y-dimension(m) z-dimension(m) well length (m)	1400 80 19.6 800
Reservoir properties Initial pressure (kPa) Initial temperature ($^{\circ}C$) Initial oil saturation Initial gas saturation	 2654 20 80 20
Rock properties Permeability (mD) Porosity	 1000 0.35
Fluid properties Deal oil Oil and gas components	

4. Results and Discussions

Fig. 5 gives the temperature profile simulated from COMSOL after 100, 180 and 365 days with the same energy input as that used in SW-SAGD process in STARS.





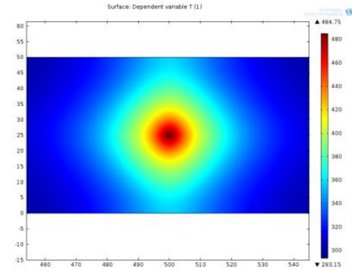


Fig. 5 Temperature profile for 2-D two phases linear flow EMH models (in COMSOL)

Cumulative oil production for the base case reservoir for cold production, EMH and SW-SAGD during approximately 3 years are in Fig. 6. The cumulative oil production from EMH increases from the beginning and increment is maintained throughout the process; however, the SW-SAGD gives smaller improvement due to the lack of mobility of the extra heavy bitumen.

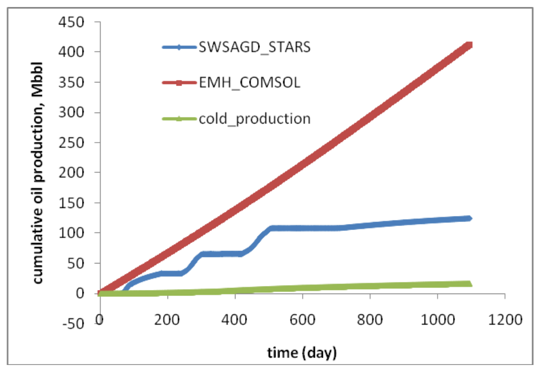


Fig. 6 Cumulative oil recovered in Mbbl for EM heating, cold production (no heating) and SW-SAGD for the base case

To investigate EMH performance compared to SW-SAGD, two cases were run for oil reservoirs, where the application of SAGD is difficult or has proven to be unsuccessful: 1) thin-pay zone, 2) low-permeability

Thin-Zone Reservoir

For this simulation, EMH is applied to a reservoir of 21 ft of thickness. All other fluid and reservoir properties were the same as for the EMH base case. SW-SAGD was applied to this reservoir using the same amount of energy input than for the EM heating case but as injected steam. Once steam is injected, it tends to rise to the top of the reservoir. For thin pay-zone reservoirs, this can occur very rapidly causing an excessive amount of heat loss through the overburden formation. Therefore, much of the energy input as injected steam leaves the reservoir before a significant viscosity reduction occurs. In contrast, when EM energy is applied the heat is produced within the reservoir instead of being transported by a fluid and does not depend on the small amount of steam created in situ when the water is vaporized if there exists. A larger recovery factor was obtained when EM heating was applied for the thin zone than for the base simulation case. This could be attributed to the same amount of energy used as power source for both cases regardless of the pore volume reduction. The results from Fig. 7 indicate that EMH could be used as an alternative recovery method to produce from thin reservoirs, where conventional thermal recovery methods such as SAGD are not cost effective.

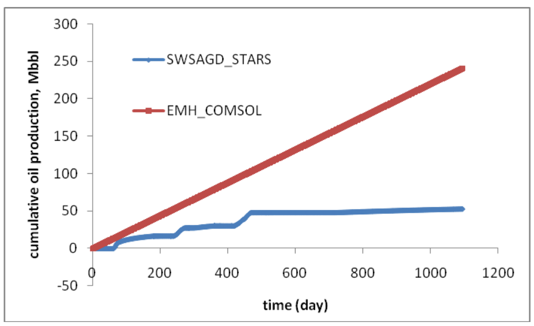


Fig. 7 cumulative oil recovered for EMH and SW-SAGD for the thin-zone (7m) reservoir simulation

Low Permeability Reservoir

For this simulation, an isotropic permeability of 20md was used. All other fluid and reservoir properties were the same used for the EMH base case simulation. Fig. 8 shows cumulative oil production obtained from EMH and SW-SAGD for a reservoir with permeability of 20 md. As can be seen, the amount of oil that is produced with SW-SAGD after a simulation period of 3 years is very similar to that produced when no heat is input to the reservoir. This is because low permeability reservoir has almost no initial injectivity. Therefore, SW-SAGD has little effect on this type of reservoir since it relies on the injection of steam to introduce heat to the formation. Simulation results showed that oil production enhancement (from cold production) using SW-SAGD for the 20 md reservoir is not effective. In the case of EM heating the reservoir is heated from within, so it is much less sensitive to a permeability reduction than SW-SAGD.

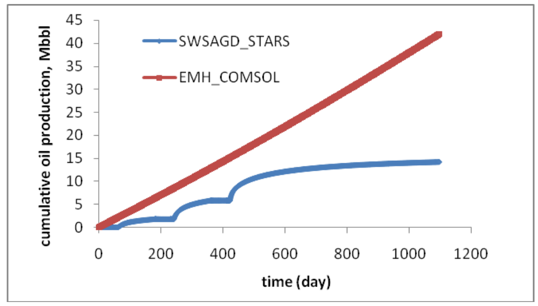


Fig. 8 cumulative oil recovered for EMH and SW-SAGD for the low permeability reservoir simulation

5. Conclusions

The main objective of this work was to develop a multiphase, two-dimensional EMH model to evaluate the response of a reservoir undergoing EMH. Numerical simulations using COMSOL Multiphysics were conducted for different fluid and rock properties for certain types of reservoir where other thermal recovery methods have been reported to fail. Also, sensitivy analysis was performed to define critical variables and their effect on EMH based on cumulative oil produced.

The EM adsorption coefficient plays an important role for EMH, which allows for the heat to penetrate further in the reservoir. Compared to ERH, EMH can operate with higher power sources and reach higher temperatures.

A sensitivity analysis performed on the electrical operating parameter showed that the higher the frequency the higher was the cumulative oil recovered. This trend was obtained for frequencies up to 915 MHz. Above this value, although very high temperature are obtained at the wellbore, there is a very low peneratration of the EM energy. Therefore, less oil is heated and mobilized.

EMH can be used as an alternative to steam injection, and yields better recovery factors especially for thin-zones and low-permeability reservoirs. It was shown that permeability changes have a smaller effect on production for EMH than for steam injection.

6. Recommendations

The model developed and cases studied contain only one well from which the EM energy is introduced to the reservoir. This reduces the ability of heating a large area of the reservoir. This model could be extended to study the performance of EMH applied in patterns.

EM adsorption coefficient is usually a function of temperature and water saturation, so the extension to the model including water phase should be considered.

For all cases, the reservoir was assumed to be homogeneous and isotropic. This might have a large impact on obtaining very uniform temperature profiles along the reservoir. Since there are not preferential paths for fluid flow or water saturation constracts, The EM energy is conducted uniformly through the reservoir avoiding the generation of vaporization spots. Therefore, reservoir heterogeneity should be included to evaluate its effect on recovery when EMH is applied.

7. References

1. Bogdanov, I., El Ganaoui, K and Kamp, A.M., Study of Electrical Heating Application for Heavy Oil Recovery, Presented at the 2008 COMSOL Conference held in Hannover (2008)
2. Butler, R.M., Thermal Recovery of Oil and Bitumen, Englewood Cliffs, N.J., Prentice Hall, 285-359 (1991)
3. Carrizales, M., Lake, L.W., and Johns, R., Multiphase Flow Simulation of Heavy-Oil Recovery by Electromagnetic Heating, Paper SPE 129730 presented at the 2010 SPE Improved Oil Recovery Symposium held in Tulsa, Oklahoma, USA, 24-28 (2010)
4. Carrizales, M., and Lake, L.W., Two-Dimensional COMSOL Simulation of Heavy-Oil Recovery by Electromagnetic Heating, Presented at the 2009 COMSOL Conference held in Boston, Massachusetts, USA (2009)
5. COMSOL Multiphysics, COMSOL Multiphysics Modeling Guide Version 4.2a (2011)
6. Computer Modeling Group, Ltd., STARS Users Guide, Version 2008, Calgary, Canada.
7. De Oliveira, H.J.M., Barillas, J.L.M., Da Mata, W., and Dutra, T.V., Energetic Optimization to Heavy Oil Recovery by Electromagnetic Resistive Heating (ERH), Paper SS-92-18 presented at the Fourth Petroleum Conference of the South Saskatchewan Section, Regina (2009)
8. Diaz-Viera, M.A, Lopez-Falcon, D.A, Moctezuma-Berthier, A. and Ortiz-Tapia, A, COMSOL Implementation of a Multiphase Fluid Flow Model in Porous Media, Proceedings of the COMSOL Conference 2008 Boston (2008)
9. Joshi, S.D., A Laboratory Study of Thermal Oil Recovery Using Horizontal Wells, paper SPE/DOE 14916 presented at the 1986 SPE/DOE Fifth Symposium on Enhanced Oil Recovery held in Tulsa, OK, April 20-23 (1986)
10. Kovaleva, L., Dabletbaev, A., and Minnigalimov, R., Recovery of Heavy Oil and Bitumen Techniques with the Radio Frequency Electromagnetic Irradiation, SPE 138086 presented at the 2010 Russian Oil & Gas Technical Conference and Exhibition, Moscow, Russia (2010)
11. McGee B.C.W. and Vermeulen, F.E., Electrical Heating with Horizontal Wells, Paper SPE 37117 presented at the 1996 SPE International Conference on Horizontal Well Technology, Calgary, Canada (1996)
12. Wattenbarger, R.A. and McDougal, F.W., Oil Production Response to in situ Electrical Resistance Heating, *J. Cdn. Pet. Tech* **27** (6), 45-50 (1988)
13. Oballa, V., and Buchanan, W.L., Single Horizontal Well in Thermal Recovery Processes, paper SPE 37115 presented at the 1996 International Conference on Horizontal Well Technology, Calgary, Canada (1996)