Simulation of Oil Sands Induction Heating using Voltage-Driven Coils with Magnetic Core

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Abstract: The most common method for in-situ recovery of oil sands is Steam Assisted Gravity Drainage (SAGD). SAGD is based on injecting pressurized steam into the ground to heat up the highly viscous bitumen and reduce its viscosity allowing oil to flow. This process is energy and emissions intensive, and consumes large quantities of water. Consequently, there has always been interest in alternative methods to recover oil sands. This work aims to investigate the feasibility of using induction heating as one of the alternatives to raise the temperature of oil sand formations to sufficient levels that allow oil production. We use the Induction Heating multiphysics interface in COMSOL to model and simulate an innovative design of a voltage-driven coil with a magnetic core to heat a resistive medium representing oil sands formations. Finally, we conclude that it is feasible to heat oil sands using the proposed induction heating coil configuration, with higher temperatures realized in formations with lower resistivities.

Keywords: oil sands recovery, electromagnetic induction heating, voltage-driven induction coil, heat transfer.

Introduction

In many oil sand formations, the conventional oil extraction method known as Steam Assisted Gravity Drainage (SAGD) is inappropriate, usually because of reduced quality of the caprock, or because the formation is too shallow to allow injection of high pressure and high temperature steam. Furthermore, SAGD is an emissions intensive and inefficient process that consumes large amounts of external water to generate the required steam, it also requires a large capital investment due to the steam generation facility.

To produce oil from formations where SAGD is not suitable and to improve the efficiency and the emissions intensity of the oil sands recovery process, alternative enhanced oil recovery methods are considered. Various electrical and electromagnetic heating methods are among these alternatives, which are often divided by operating frequency and heating mechanism to, resistive, inductive and microwave heating. Resistive heating is based on the Joule heating effect and is typically in the low frequency range, induction heating makes use of eddy current heating within the mid-range frequencies and microwave heating is a high frequency dielectric heating process. Induction heating presents an advantage over resistive heating in that it does not require direct electrical contact with the formation, direct electrical contact with the formation results in the generation of hot spots around the electrodes leading to lost electrical connections. Similar to microwave heating, practical penetration depths can be achieved with induction heating. Multiple studies have been performed on resistive and microwave heating for heavy oil and oil sands production [1][2][3][4][5], however, induction heating has had limited studies mainly because of the difficulty of implementation. Because of the aforementioned advantages of induction heating, and the limited studies available in comparison to resistive and microwave heating, we decided to study induction heating as a stand-alone recovery method or as pre-heat to steam injection using a design that is easy to implement.

The Induction Heating multiphysics interface, which includes the Magnetic Fields and Heat Transfer interfaces, is used to study a two-dimensional axisymmetric model solving for magnetic fields and heat transfer iteratively. The goal is to determine power loss in the oil sands domain due to ground currents and consequently determine the temperature in the oil sands. The oil sands are assumed homogeneous with initial resistivity swept over values representative of the Athabasca oil sands, the resistivity then varies linearly with temperature after each time step. The resistivity of the oil sands comes from the connate water that is part of the oil sands composition. The foundation of this study is the lab scale results on the possibility of heating water using electromagnetic induction [6]. The next step is coupling a reservoir simulator to the Magnetic Fields interface and computing energy to oil ratio.

Theory

According to Ampère's law, an alternating electric current passing through an electric conductor generates an alternating magnetic field around that conductor. Faraday's law states that an alternating magnetic flux in a loop of wire generates an induced voltage in that loop. Furthermore, any electric current flowing through a conductive medium will dissipate energy in that medium in the form of heat, the power dissipated depends on the amount of current and the resistivity of the medium.

The alternating current within the induction coil creates a magnetic field in the oil sands formation, and as a result, electric currents are induced in the oil sands in the form of a ground current loop and the power is dissipated in the form of heat. The ground current and the heat generated are directly proportionate. Figure 1 shows a schematic to help describe the induction heating process in an oil sands formation.

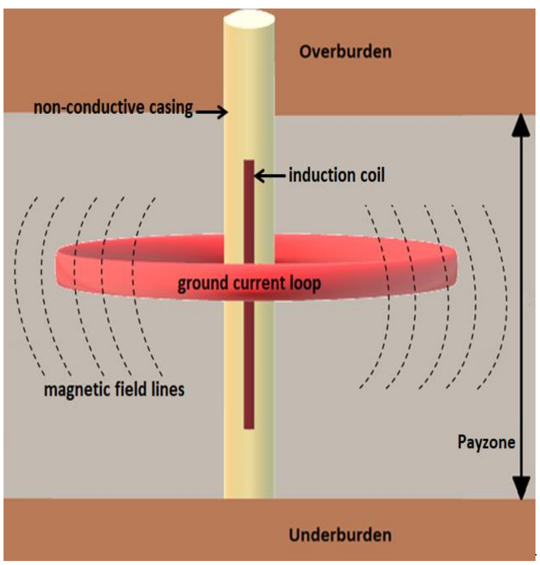

Figure 1. Schematic describing the application of induction heating in oil sands.

Model Description

The problem is modeled as a transformer where the induction heating coil is the primary of the transformer and the formation is the transformer secondary. The secondary is essentially a single turn inside the formation, and to achieve maximum voltage across the secondary the number of primary windings should be as low as possible, single turn primary is the best possible scenario. A magnetic core will increase the magnetic flux density, and therefore, we can achieve higher power density in the oil sands domain for the same input power used with an air core coil. Moreover, to increase the penetration depth of the magnetic flux in the oil sands domain and achieve heating as far as possible away from the transformer primary, it is required to have a longer coil. A longer coil will result in a longer flux return path, however, with a single turn primary that is a bit of a challenge.

To accommodate an extended length coil as a single turn primary equivalent of a transformer, we connected several single turn voltage-driven windings in parallel. This allows the magnetic flux to go through a longer return path in the oil sands domain while maintaining a uniform flux distribution in the magnetic core, minimizing leakage flux, and preserving a single turn in the primary equivalent of a transformer to achieve maximum possible voltage in the oil sands. The current in these single turns is not evenly distributed, it depends on the position of the winding in respect to the coil, outer windings carry most of the current and the inner windings carry less the current. The number of windings depends on geometry size, wire diameter, and the input power. In addition, the magnetic core is extended beyond the wound length to improve the magnetic circuit characteristics and reduce the input power required to achieve the same heat distribution and power density in the oil sands.

In brief, the model is simply a vertically positioned coil in a non-conductive casing surrounded by a homogeneous oil sands domain. The coil consists of a core with enhanced magnetic permeability, and multiple discrete voltage-driven single turn windings to achieve a uniform distribution of magnetic flux throughout the core. The magnetic core extends longer than the windings to minimize magnetic flux leakage ensuring the longest possible flux return path in the oil sands domain and hence, pushing heat penetration further into the oil sands.

Since the coil geometry is symmetric, the model is built as a two-dimensional axisymmetric model with normal size physics-controlled mesh as shown in Figure 2.

The Magnetic Fields interface is used to compute the induced current in the oil sands as a result of the magnetic fields generated by the coil in the frequency domain. The operating frequency is investigated by a parametric sweep over a wide range of values up to several Megahertz.

The Heat Transfer interface is used to model heat transfer and temperature distribution in the oil sands in the time domain. The oil sands domain follow a linearized resistivity conduction model with a resistivity temperature coefficient of 0.023 per Kelvin. The Frequency-Transient study is used to compute temperature changes over a period of one-hundred days with single-day time steps, in addition to the electromagnetic field distribution in the frequency domain.

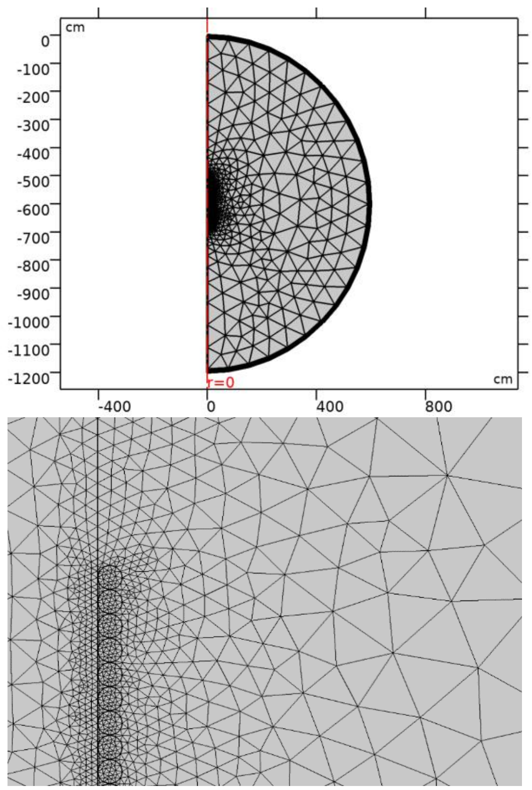

Figure 2. Normal size physics-controlled mesh of the geometry with a zoom-in view of the mesh elements.

Computational Methods

The Induction Heating multiphysics interface, which includes a Magnetic Fields and a Heat Transfer interface, is used to model induction heating of the oil sands. The electromagnetic power dissipation is the heat source in the coupled multiphysics and the oil sands domain material properties depend on temperature.

Maxwell's equations are solved in the Magnetic Fields interface to compute the induced currents and the electromagnetic loss density at a specified voltage and frequency excitation. The electromagnetic loss density from the Magnetic Fields interface is then coupled to the Heat Transfer interface as the heat source to estimate the temperature distribution in the oil sands domain. This process is performed iteratively over a defined heating period.

The resistivity of the oil sands is updated after each time step according to a linear relationship with the temperature computed at the previous time step. Figure 3 shows a flowchart of the induction heating simulation in COMSOL.

The simulation allows to accurately predict the magnetic field distribution, power dissipation, and temperature distribution at any given input voltage and operating frequency. The coupled multiphysics simulation is governed by the following equations:

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \mathbf{u} \cdot \nabla T = \nabla \cdot (k \nabla T) + Q_e$$

$$Q_e = Q_{rh} + Q_{ml}$$

$$Q_{rh} = \frac{1}{2} Re(\mathbf{J} \cdot \mathbf{E}^*)$$

$$Q_{ml} = \frac{1}{2} Re(j\omega \mathbf{B} \cdot \mathbf{H}^*)$$

where,

ρ is the density of connate water in kg/m^3

C_p is the heat capacity in J/(kg.K)

k is the thermal conductivity in W/(m.K)

$\mathbf{u}$ is the velocity field

T is the temperature in Kelvin

Q_e is the electromagnetic loss in W/m^3

Q_{rh} represents the resistive losses

Q_{ml} represents the magnetic losses

J is the induced current density Amp/m^2

E is the electric field density in Volt/m

ω is the operating frequency in Hertz

B is the magnetic flux density in Tesla

H is the magnetic field intensity in Amp/m

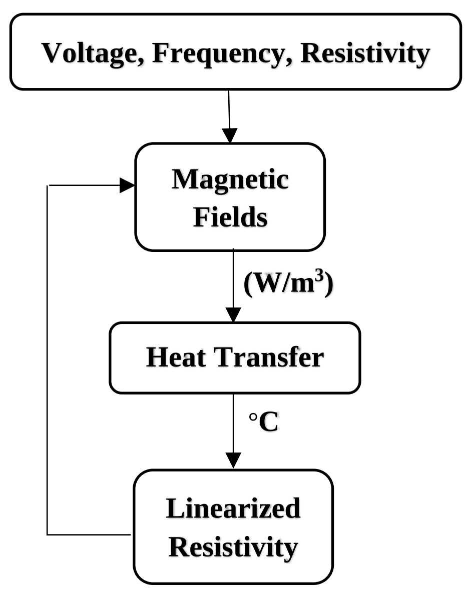

Figure 3. Simulation Workflow in COMSOL.

Results and Discussion

The multiphysics simulation covered a heating period of one-hundred days with single-day time steps, the oil sands initial resistivity was swept over a range of values from 100 Ω·m to 1500 Ω·m to represent the resistivity values of the Athabasca oil sands. The operating frequency was swept from 100 kilohertz to 5 Megahertz. The voltage to drive the coil was 10 kilovolts, which resulted in a magnetic field density of 0.2 Tesla inside the magnetic core at 1 Megahertz.

As the heating progresses, it is observed that the near wellbore region dries out and the majority of the heating front moves further away from the wellbore. It is also noticed that in the first few days the temperature increases rapidly near the wellbore, subsequently, the heat penetration slows down towards the end of the simulation. This suggests that the maximum penetration depth may be reached quickly, however, beyond this depth heating will most likely occur through other heat transfer mechanisms. The operating frequency has no direct influence on the temperature distribution in the oil sands domain. The increase of frequency reduces the magnetic field magnitude, thus decreasing the required magnetizing current and input power while maintaining temperatures in the oil sands domain. Therefore, the higher the frequency the less input power required, this can be observed by the drop in total current withdrawn by the windings and the reduced magnetic flux density inside the magnetic core. For lower frequencies higher magnetizing current is required for the same magnetic field density values, and hence, more input power required.

The initial resistivity of the oil sands is the main parameter affecting the temperature distribution. At a lower initial resistivity, the induced currents in the oil sands are higher, and therefore, more heat is generated in the formation leading to higher temperatures further away in the oil sands. Figure 4 shows the power density distribution in the oil sands domain for a 300 Ω·m oil sands domain at 1 Megahertz. Figures 5, 6, 7, and 8 show the temperature profiles for a 300 Ω·m oil sands domain at 1 Megahertz after 5, 35, 70 and 100 days of heating respectively. Figure 9 is a plot of the radial distance heated to $100\,°C$ versus initial resistivity of the oil sands domain. This is the boiling temperature for water at atmospheric pressure and for underground steam generation a higher temperature is needed as the boiling temperature will rise with the increase of pressure.

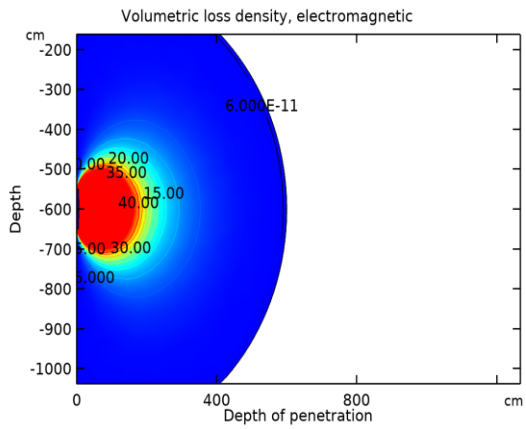

Figure 4. Power density (Watts/m^3) in a 300 Ω·m oil sands domain at 1 MHz.

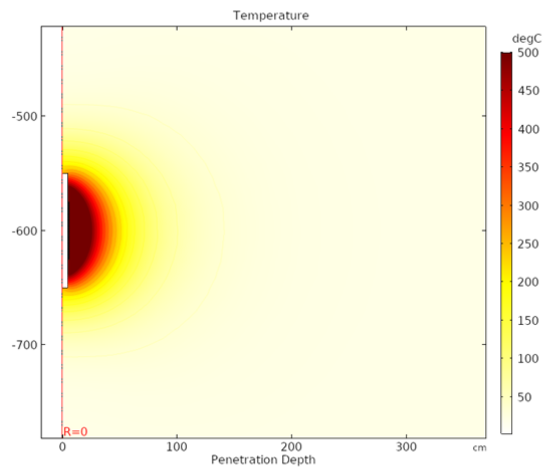

Figure 5. Temperature distribution in a 300 Ω·m oil sands domain at 1 MHz after 5 days of heating.

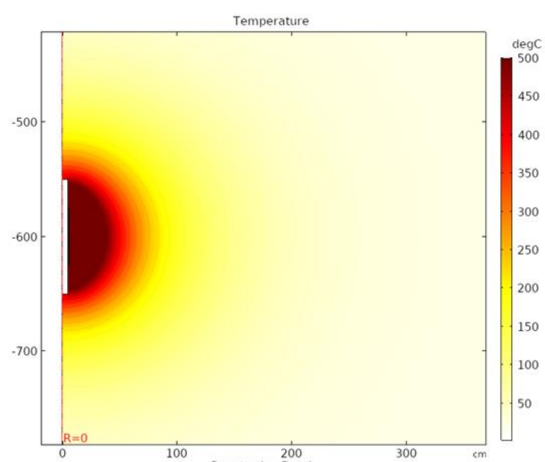

Figure 6. Temperature distribution in a 300 Ω·m oil sands domain at 1 MHz after 35 days of heating.

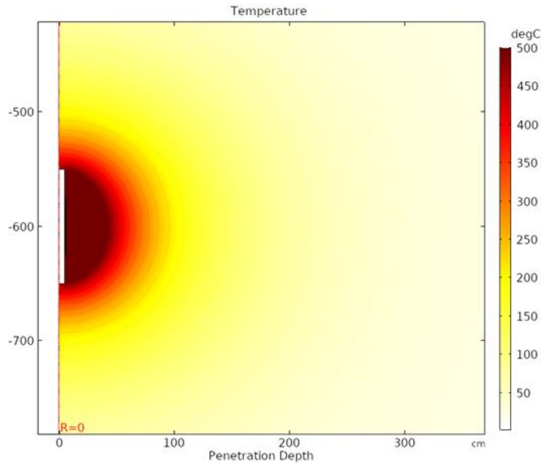

Figure 7. Temperature distribution in a 300 Ω·m oil sands domain at 1 MHz after 70 days of heating.

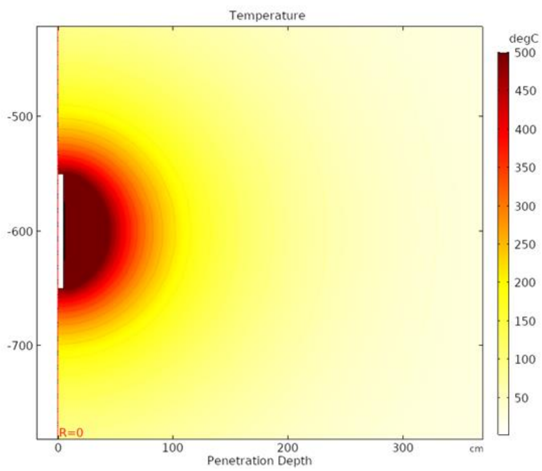

Figure 8. Temperature distribution in a 300 Ω·m oil sands domain at 1 MHz after 100 days of heating.

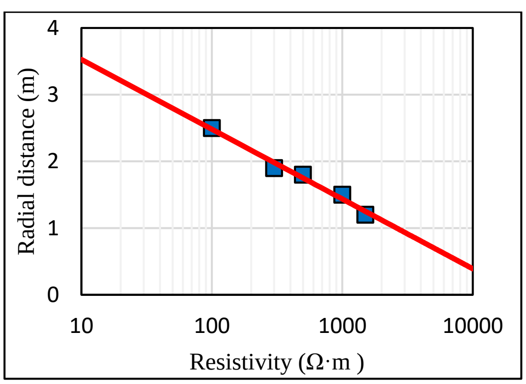

Figure 9. Radial distance heated to 100 $°C$ for different initial values of oil sands resistivity. Blue squares are computed radius values from simulation and the red line shows extrapolated radius results.

Conclusions

The simulations demonstrate the feasibility of using voltage-driven coils with magnetic core to heat oil sand formations to levels comparable to steam associated methods. Induction heating of oil sands is more effective in formations with lower resistivity.

The operating frequency does not have a direct impact on the heat penetration inside the oil sands, but rather it affects the magnetic flux density and ultimately the coil input power.

Building on this study, we have started the process of coupling the Magnetic Fields interface to a reservoir simulator in order to determine the energy to oil ratio in a heterogeneous oil sands formation.

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