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Interaction of Electromagnetics with Geology for Thermal Treatment of Heavy Petroleum

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Summary

Heavy petroleum is a term commonly applied to describe crude oils with specific gravity less than about 0.935 (~20° API). These oils, which include oil sand “bitumen”, are not readily producible by conventional techniques. Their viscosity is so high that the oil cannot easily be mobilized and produced conventionally by a pressure drive. Therefore, a recovery process is required to reduce the viscosity enabling the oil to be produced.

Thermal recovery methods as applied in heavy petroleum reservoirs have the common objective of accelerating the recovery process. Raising the temperature of the host formation reduces the heavy oil viscosity, allowing a material that is nearly solid at ambient temperatures to flow as a liquid. In conventional thermal recovery techniques, steam or steam-solvent mixtures are injected to reduce the viscosity of the petroleum and to allow it to flow into a producing well. Cyclic steam stimulation (CSS) and steam-assisted gravity drainage (SAGD) methods are among this class of recovery methods. It is recognized that such recovery methods can be costly to implement and operate and that they commonly require access to significant water resources.

The effectiveness of steam injection methods is limited commonly by depth, due to lithostatic containment requirements. These techniques are adversely affected by heat losses in surface steam lines and the wellbore that reduce the efficiency of steam heating processes with a negative impact on the oil production rate and project economic performance. There are specific situations where steam injection-based techniques may not perform well, especially in:

- Thin pay-zones, where heat losses to adjacent (non-oil-bearing) formations may be significant.
- Low permeability formations, where the injected fluid may have difficulty penetrating deep into the reservoir.
- Heterogeneous reservoirs, where high permeability streaks or fractures can cause early fluid breakthrough and reduced sweep.

An alternative thermal technique for viscosity reduction of oil sands/heavy oil uses electromagnetic (EM) energy that can potentially overcome some of these limitations [1]-[14]. EM-based in-situ thermal treatment processes are viable alternatives to steam-based processes because electrical instruments and power supplies are widely available requiring a minimal surface presence, which favors their use in populated areas or offshore sites. These thermal recovery techniques are generally unaffected by initial formation injectivity, heat transfer, and lithological barrier between oil-rich reservoirs, reservoir containment, and the conformance management of injected fluids or gases, all of which have negatively impacted other thermal recovery processes such as SAGD. In addition, EM-thermal recovery has advantages compared with other recovery technologies including [1]-[14]:

- In-situ heat generation.
- Reduced water- cut.
- Heat transfer independent of formation permeability structure.
- Depth independence.
- Lack of hazardous chemical management.
- Improved permeability resulting from thermal dilation accompanying rapid heating.
- Competitive to superior cost structure compared to steam-based methods..
- Instantaneous heating that is independent of formation thermal conductivity.

EM energy can trigger two different phenomena in a reservoir formation, electro-thermic and electro-kinetic mechanisms. The electro-thermic mechanism refers to the heat produced from the absorption of electromagnetic energy by reservoir materials at a molecular level that involves electric conduction and/or dielectric polarization, depending on the electromagnetic source frequency. Electric conduction dominates when a DC or a low frequency current source is applied resulting in Joule heating. In this low frequency regime, charged particles moving in an electric circuit formed within the reservoir formation are accelerated by an electric field but they give up some of their kinetic energy as a result of particle collisions. The increased particle kinetic energy manifests itself as heat increasing the temperature of the conducting material, which in this case, is the electrolyte fluid of the subsurface formation.

With a higher frequency electromagnetic source however, the dielectric heating prevails in which dipoles formed by the molecules tend to align themselves with the electric field (this is called polarization) with a velocity proportional to the frequency of the alternating fields. However, inter-particle resisting forces restrict the motion of these polar molecules and limit the mobility of molecules and generate random motion, which is essentially heat. Dielectric heating can be efficient as illustrated by microwave ovens. The key requirement for dielectric polarization is that the frequency range of the external oscillating field should enable adequate inter-particle interaction. The larger the masses involved, the slower the response upon applying or removing of the external EM field. As the frequency increases, the slower polarization mechanisms of heavier particles lags. The dependency of characteristic relaxation frequency and particle mass indicates that heating is achieved mostly by polarization mechanisms and local charged particle oscillations at higher frequencies. In contrast, as the frequency decreases, the free charge/ionic conduction plays an increasingly dominant role in the heating process.

Skin effect, the exponential decrease of EM field penetration into materials, needs to be considered for electro-thermal processes. In any EM thermal process the choice of the electromagnetic source frequency represents a compromise between fast heating (greater heat rate) and penetration depth. Lower frequency EM fields penetrate deeper into the reservoir but they produce a lower heat rate. High-temperature superconductive transmission lines have reduced the heat loss that increases the efficiency of low-frequency EM thermal treatments [15].

Low frequency EM heating of a reservoir depends directly on the continuous conductive path between electrodes (introduced above as the electric circuit). This requires that connate water to be liquid, especially around the electrodes. This connate water can be an undesirable sink for input high frequency EM energy and it is desirable to reduce the near source loss of energy into the connate water at the expense of energy penetration deep into the reservoir. In the unlikely event that the area around the EM source is dry, high frequency EM waves (such as microwaves) can propagate effectively through water-free reservoir regions to achieve remote energy transfer. However the electric circuit cannot be formed in water-free zones, which make the heating by low frequency sources ineffective. In this regard, a medium frequency EM source has the benefits and advantages of both low and high frequency sources where both electric conduction and dielectric polarization mechanisms contribute the heating process. In a reservoir, such a medium frequency EM source (for example, the lower part of the radio frequency-RF band) can result in Joule heating until the formation of a vapor facilitates dielectric heating after the in-situ water is evaporated. One key advantage of using an RF source is the capability of directing the EM energy toward the area of interest in the subsurface by using an array of RF sources that can provide a targeted heating that transfer energy more efficiently [16],[17]. Some simulation results will be discussed on this during the presentation.

The electro-kinetic mechanism on the other hand, relies on the coupling of mechanical (acoustic pressure) and electromagnetic energies in wet porous rocks. Electro-kinetic phenomenon arises in the subsurface from the bound charges on a solid surface in contact with an electrically conductive fluid, where the electric charges separate into an electric double layer (EDL). The inner layer consists of ions adsorbed onto the solid surface, while the outer layer is formed by ions under the combined influence of ordering electrical and disordering thermal forces. When a fluid-saturated porous medium is exposed to an external low frequency electromagnetic field, an electric current, the streaming current, will be produced by electromagnetic forces applied on the outer ionic layer of the EDL. This creates a mechanical disturbance and a pressure gradient in the fluid. By taking this effect into account, the pressure response resulting from low frequency EM energy can be modeled and it can contribute to fluid flow in the porous medium enhancing the heavy oil recovery process.

In addition, these multi-physics phenomena can also fracture the formation [18]-[20], which itself is another application of EM energy methods.

Efficient fracturing methods are of interest for enhancing petroleum recovery in some instances and hydraulic fracturing is a commonly employed reservoir stimulation technique.

Electromagnetic energy provides a potentially new mechanism for fracture initiation and propagation using the joint rapid thermal-electrokinetic pressurization mechanisms. The pore pressure resulting from the electro-thermal expansion of pore fluids and the electrokinetic mechanism may not be balanced with the fluid flow and the fluid volume increment resulting from pore-space dilation. When the pore pressure is created relatively quickly then, it can lead to failure of formation rock and the creation of micro-cracks and fractures.

The formation electrical properties are continually changing before and during the electromagnetic interaction due to reservoir heterogeneities. This is one of the main challenges of EM-based in-situ processes that should be considered during the selection and deployment of the EM sources. It is therefore essential to have a good understanding of electrical properties (dielectric permittivity and dynamic resistivity) for the design and optimization of any EM-based in-situ thermal treatment. The parameters dictate the operating frequency, electrode or antenna sizes, shapes and spacing as well as the operating voltage, current and power levels. Moreover, they also determine heating rates, system operating efficiencies, and overall electrical energy requirements.

Sufficient data must be collected from standard reservoir characterization tools (i.e. well logs etc.) to clarify the dependency of the electrical properties on density, frequency, moisture content and temperature and to indicate how the laboratory results could be extended to estimate the electrical properties of a natural petroleum accumulation.

We use the previously determined, generic electrical properties of Athabasca oil sands [21] for modeling and design purposes. This data could be profitably updated using new methods and instruments with more recent core measurements and well-logs intended for EM-based thermal treatments.

We shall review both available EM-thermal technologies such as ET-DSP [22] and ESEIEH [23] and the industrial numerical simulation capabilities [24]-[27].

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