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# A comparative study of oil sands preheating using electromagnetic waves, electrical heaters and steam circulation

Asghar Sadeghi [a], Hassan Hassanzadeh [a,*], Thomas G. Harding [b]

[a] Department of Chemical and Petroleum Engineering, Schulich School of Engineering, University of Calgary, 2500 University Drive NW, Calgary, AB T2N 1N4, Canada
[b] Nexen Energy ULC, 801 7th Avenue SW, Calgary, AB T2P 3P7, Canada

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ABSTRACT

Application of steam assisted gravity drainage (SAGD) requires a time period between three to six months to establish fluid communication between the horizontal wells in a well pair. During this period, conductive heating reduces the bitumen viscosity such that it turns fluid and producible. High frequency electromagnetic waves may be used to enhance the heating process by in situ generation of thermal energy resulting from polarization of electrically conductive molecules inside the oil sands. We present new analytical solutions for three different preheating (start-up) scenarios including: steam circulation in well-pairs, electrical heaters in both horizontal wells, and electromagnetic antenna in the injector and electrical heater in the producer. The three scenarios are compared based on the time required for bitumen mobilization and the energy usage. Results show that the electromagnetic heating (EMH) decreases the energy usage significantly. The findings reveal that EMH in the frequency range of 1–10 MHz results in temperatures in the vicinity of the well that are below the coke formation temperature and thus coke generation and formation damage can be minimized. These results find applications in pilot and field scale implementation of EMH for recovery of bitumen from oil sands.



## 1. Introduction

The main problem associated with bitumen production is its high viscosity. Thermal methods based on steam injection have been proposed and implemented in the last decades to decrease the viscosity and produce the bitumen. For Athabasca oil sands, the commercialized thermal method is steam assisted gravity drainage (SAGD) technique proposed by Butler [1]. This method uses two parallel horizontal wells about 1 km in length drilled 5 m one above the other at the base of the productive zone. The upper well is the injector and used to inject steam and the lower is used to produce the heated oil. The injected steam rises in the reservoir due to its buoyancy and forms a steam invaded zone that has an inverted triangular cross section or so called steam chamber. The steam releases its latent heat to the formation at the edges of the steam chamber and eventually condenses. The mobilized oil and the condensed steam drain toward the production well and are lifted to the surface. Detailed theory of SAGD is presented elsewhere [1].

Before the bitumen production stage, fluid communication needs to be established between the two horizontal wells that allows steam injection and oil drainage. Since the bitumen between the two wells is highly viscous initially this communication is only possible by heating it so that it turns fluid. This requires that the viscosity of bitumen in the vicinity of wells be decreased by several orders of magnitude. It is common practice to circulate steam in both wells for a three to six month period to heat the formation around the wellbores and thereby reduce the bitumen viscosity making it mobile. Lack of bitumen production during the start-up motivated operators to minimize this period and accelerate the onset of production. Application of SAGD is known to be energy intensive and associated with environmental impacts, especially for thin and low quality oil sands reservoirs [2].

Ultrasonic-based method has been also examined to improve the oil recovery, where ultrasonic generator and transducer operating at 20 kHz and 350 W of power were used [3,4]. Another alternative is Electrical Heating (EH), which utilizes downhole electrical heaters to heat the formation around the wellbore and mobilize the bitumen [5]. Electromagnetic Heating (EMH) with different range of frequencies has also been suggested for heating of oil sands [6]. EMH can be categorized into low frequency heating (electrical resistive heating, <100 Hz), medium frequency heating (induction heating, <300 kHz) [7] and high frequency electromagnetic heating such as radio frequency (between 10 and 100 MHz) and microwave (between 100 MHz and 100 GHz) [8]. Different

* Corresponding author.
*E-mail address:* hhassanz@ucalgary.ca (H. Hassanzadeh).

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**Nomenclature**

| Parameter | Definition (Unit) |
|---|---|
| $\alpha_{em}$ | attenuation factor (or absorption coefficient) (1/m) |
| $\varepsilon_0$ | electric permittivity of the vacuum (F/m) |
| $\varepsilon$ | electric permittivity of the medium (F/m) |
| $\zeta_D$ | dimensionless radius (–) |
| $h$ | vertical well spacing (m) |
| $k_T$ | effective thermal conductivity (W/mK) |
| $L$ | horizontal length (m) |
| $M_t$ | volumetric heat capacity (J/m$^3$ K) |
| $\mu_0$ | magnetic permeability of the vacuum (H/m) |
| $\mu$ | magnetic permeability of the medium (H/m) |
| $\mu_o$ | oil viscosity (*cp*) |
| $N$ | Stark number (–) |
| $P_g$ | gauge pressure (MPa) |
| $P_0$ | power (W) |
| $\dot{q}_{em}$ | volumetric heat generation (W/m$^3$) |
| $q$ | heat rate (W) |
| $q_{inj}$ | injection well heat rate (W) |
| $q_{prd}$ | production well heat rate (W) |
| $r$ | r-direction (Radial) (m) |
| $r_w$ | wellbore radius (m) |
| $r_e$ | outer radius (m) |
| $\sigma$ | medium conductivity (S/m) |
| $T$ | temperature (K) |
| $T_0$ | initial temperature (K) |
| $T_s$ | steam temperature (K) |
| $T_{inj}$ | injection well temperature (K) |
| $T_{prd}$ | production well temperature (K) |
| $t$ | time (s) |

*Subscripts*

| | |
|---|---|
| $D$ | dimensionless parameter (–) |
| $e$ | external diameter |
| *em, E* | electromagnetic (–) |

radio frequency and microwave ranges have been reported in the literature; for example, microwave range is reported to be between 300 MHz and 300 GHz in [9]. In this study, we assume that the applied frequency is in the high frequency range (higher than 0.3 MHz). The mechanism of high frequency heating is the flipping motion of molecules caused by waves which is called "dipole friction of molecules" [10]. The mathematical formulation of electromagnetic heating was proposed by Maxwell [11,12]. It can be simplified to Beer-Lambert's law and coupled with the thermal energy balance [13,14].

Abernethy [15] developed an elegant analytical model based on the Beer-Lambert's power formulation to find the temperature distribution from the radiation of electromagnetic energy in a radial oil reservoir. Steady-state flow performance of a vertical well was compared to an unheated case. The results of a transient flow condition and some practical aspects of EM heating were also presented and discussed. Heat conduction and heat loss to the surrounding formations were considered negligible.

Fanchi [16] developed a method for estimating the temperature increase associated with reservoir electromagnetic heating. An asymptotic solution to the Maxwell's equations was presented and it was nicely shown that for an axially symmetric wave, which is propagating radially, the power attenuation follows the Beer-Lambert's law. Then, a simple energy balance model has been developed and coupled with the Beer-Lambert's law to model the EM heating processes. This model accounts for the heat loss to the confining strata while the conduction in the reservoir has been ignored.

Carrizales et al. [17] presented a single-phase and steady-state model with the Beer-Lambert heat source to find the temperature profiles and the oil productivity improvement. They considered both counter-current flow where the source antenna is placed in the production well and co-current flow where the flow is taking place in the same direction as EM wave propagation. Their steady-state results for counter-current flow have shown a relative well productivity index improvement of 2.5–12.0 as compared to cold oil production with an input power of 20–150 kW. Productivity improvement showed a peak when plotted against the absorption coefficient (attenuation factor), revealing the importance of this coefficient.

Davletbaev et al. [10] developed a single phase two dimensional *(r, z)* model for electromagnetic heating. The Beer-Lambert's law was used to describe the power source. The developed model tends to follow Carrizales et al. model [18]. Sultenfuss et al. [19] invented a method for start-up period of a SAGD well-type. They introduced their method in different schemes in which a solvent with high absorption coefficient (e.g., polar solvents like alcohols and ketones) is soaked and heated simultaneously with a high frequency antenna. After heating period, the solvent was squeezed into the oil sand reservoir and both the solvent dilution and temperature increase led to viscosity reduction. They claimed that the method can decrease the start-up period to about one month.

In a review, Rehman and Meribout [9] compared the conventional and electrical enhanced oil recovery methods. They emphasized the ability of microwave heating as an alternative for steam based recovery techniques, especially for highly permeable heavy oil reservoirs. In a recent review, Bera and Babadagli [20] concluded that EMH is a feasible method to introduce heat for the recovery of heavy oil reservoirs. Increasing the absorption coefficient of porous media by adding nanoparticles are recommended in their study. It was noted that for shale oil reservoirs, which are very tight, EMH can be a promising alternative to steam-based recovery methods. Recently, Sadeghi et al. [21] reported analytical solutions for high frequency heating of lossy geological media. The analytical solutions can be used to model the preheating period while the high frequency electromagnetic waves is used to heat the reservoir. They also introduced a method for calculation of efficient power and absorption coefficient.

There are numerous of studies on performance of SAGD including start-up period [22] and energy evaluation [23], and steam chamber development phase [24]. However, it is interesting to note that an analytical model that takes into account the simultaneous heating of SAGD well-pair is lacking. Duong et al. [22] presented an analytical solution for constant heat flux and then used a time equivalent function to apply the developed solution for constant temperature case. Ghannadi et al. [25] presented a comparative study of SAGD start-up with electrical methods. They proposed analytical solution for SAGD start-up using steam circulation based on the Duong et al. model [22]. As a second alternative method they compared the induction heating method with steam circulation. They concluded that start-up duration for the latter case is around 30% less than the former one.

Electrical heating using the downhole electrical heaters has been investigated analytically by Hassanzadeh and Harding [5] and numerically by Rabiei et al. [26]. They showed that in-situ electrical heating assisted with solvent and water is more efficient