WHY THE RADIO FREQUENCY HEATING MAY BE ATTRACTIVE FOR BITUMEN RECOVERY

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Abstract

Extra-heavy oil, bitumen and tar sand resources are increasingly explored and exploited by major petroleum companies. Production of oil from such resources is mainly done via reservoir heating, the steam injection being the most widely used technique for this. However the steam injection is not always the best suited method, for instance, in case of shallow or too deep reservoirs. One of most interesting alternatives to it is the electromagnetic (EM) heating assisted oil recovery.

Different physical mechanisms underlie the heating depending on the frequency of electromagnetic (EM) field. Low-frequency heating (LFH) is based on the Joule effect, well-known for environmental applications and has been field-tried recently. Inductive heating (IH) is the process where Foucault (eddy) currents generated within a load result finally in Joule heating. At last, high-frequency heating (HFH) is in fact the in-situ dielectric (microwave) heating resulted from rotation with friction of polar molecules in the EM field. Nevertheless, each of the mentioned methods relies on electric properties of water and can't work without some initial water amount in the reservoir.

Extra-heavy oil production via radio-frequency heating (RFH) is addressed in our current work. Under "radio" we understand the frequency range 0.1-10 MHz which formally may include in-situ IH effect. The inherent advantage of RFH based methods of oil recovery (compared to the LFH), stems from the fact that the steam chamber development may take place during production period. To analyze the RFH application for typical Athabasca bitumen deposits, the numerical simulations have been done where the heating power distribution is defined from the Maxwell equations, and subsequent coupling with dedicated reservoir simulator is performed.

After relatively short preheating period the oil production is done mostly by gravity drainage. The well pattern (including electromagnetic and production ones), the reservoir thickness, initial water amount, total power and frequency of the applied EM field - the impact of these and other physical problem parameters on efficiency of oil production is considered and discussed along with some questions specific to relevant numerical modeling.

Comparison to other thermal methods is provided. The general conclusions summarize the appraisals and indicate possible process improvements as a result of combination of operational conditions favorable to efficient production.

The current analysis of RFH assisted extra-heavy oil production is an important feature in future process design considerations.

Introduction

The global need in new energy sources may be to a large extend covered by heavy and extra-heavy oil-fields in Canada, Venezuela and, probably, in Russia. Generally speaking, the development of novel or at least, the considerable improvement of existing technologies is required to provide the necessary oil production dynamics.

Widely used thermal methods can provide sufficient oil recovery enhancement which is due to substantial decrease of the reservoir oil viscosity at elevating temperature. Being the most popular among thermal methods the steam injection is not always successfully applicable for real heavy oil reservoir conditions. Among the common reasons for that are the prohibitive heat loss from injection wells and from a reservoir, low reservoir injectivity, especially, for bitumen deposits, steam leakage, GHG emission and other environmental problems. Yet a good alternative to the steam injection has been known for decades and even field-tested. This includes a variety of methods called generally an electric or electromagnetic heating (EMH).

Recently, the methods have been studied as a recovery technique to be applied to hydrocarbon reservoirs, such as heavy oil, bitumen, tar sands, or oil shale. For latest works one can see, *e.g.* McGee and Vermeulen [1], Koolman et al. [2], Carrizales et al. [3], Davletbaev et al. [4]. Before these studies, although related to experimental results but mainly numerical, the EMH has been experimentally (more frequently) and few times field tested during three decades.

One of the most known activities on the EMH based oil recovery from tar sands took place at the Illinois Institute of Technology Research Institute (IITRI) since late 1970's up to late 1980's. Bridges et al. [5] carried out extensive program of research work on the use of EMH for different deposits. They pointed out the possibility of taking benefit of in situ upgrading and reservoir pressurization by increasing the reservoir temperature above the vaporization point of fluids using HF heating. They proposed also the so-called IITRI process, a recovery method field-tested in the Utah tar sands. After the preheating period, once the reservoir has been volumetrically heated, the oil viscosity must be low enough to facilitate the production phase first by gravity drainage and later on by a displacement mechanism, making use of the same electrodes as injector or production wells. Bridges et al. [5] tested the IITRI process in application to bitumen reservoirs with initial bitumen viscosity about 10^6 cp which then reduced to 102 cp by heating the hydrocarbon deposit to about 150 °C. Net energy ratio was estimated between 5 to 12 depending on the reservoir properties and the process conditions. Accordingly the energy requirement was in the range of 75 to 150 kWh per barrel (4.3 to 8.4 GJ/m^3) while the recovery factor was between 30 and 70 %.

Sresty et al. [6] presented laboratory and pilot scale investigations to demonstrate the RF-utility by IITRI. Two field scale experiments were conducted in Utah tar sands deposit of total volume 25 m3 resulting in approximately 35% of oil recovery in a period of 3 weeks. In addition, the laboratory experiments were done to identify the production driving mechanism. Reported recovery factor was up to 50 % for the gravity drainage, 65 % for the autogenous drive, and up to 80% for the fluid replacement. The gravity drainage experiments demonstrated a rapid recovery rate when core samples were heated more than 100°C. The autogenous drive experiment showed the beneficial effects on the recovery and quality of the produced oil because the steam and the hydrocarbon vapor were generated at temperature reaching (and exceeding) the evaporation temperature.

Vermeulen and Chute [7] carried out a research program focused on the experimental measurement of reservoir thermal and electrical properties. Conductive and inductive heating experiments were done, in particular, aimed at monitoring the temperature distribution in different planes of a laboratory sample. More uniform heating of the payzone has been observed during inductive heating.

McPherson et al. [8] described the concept of the Electromagnetic-Flood process. The authors proposed to use horizontal wells as wave guides to facilitate the energy injection. They have assumed that the evaporation of the connate water produces a vapor chamber that extends progressively as the heating and production progress in time. To accelerate the oil production, they proposed to enhance the recovery with gas injection at the top of the reservoir in addition to steam generated inside from the connate water. Numerical analysis showed that after 2 years of operation is possible to obtain a heated region up to 200m length, with an average temperature in the order of 100°C, and a total cumulated production by gravity drainage between 800 to 1000 barrels (i.e. about 0.15 m^3/day).

Kasevich et al. [9] presented proof-of-concept results for single well RFH, the downhole applicator having used a generator operating at 25 kW and 13.56 MHz. Three observation wells were drilled for monitoring temperature and magnetic measurements. The monitored temperature rate revealed a progressively decaying tendency during the operation time; starting from 3°C/h after 2-3 days, diminishing to 0.8°C/h after 1-2 weeks, and 0.2 °C/h after 4-5 weeks. The application of the EM energy was controlled with the help of specialized software capable to compute the radiation pattern.

Recently, Koolman et al. [2] and later Wacker et al. [10] have described the technical principles of the EM-SAGD process (steam or gas injection assisted by the inductive heating via so-called Litz cable). Inductive heating was evaluated using a laboratory scale EM source with working frequency of 142 kHz. After a short heating period (10 minutes) at a power of 7.2 kW, a temperature rise of 7.5K was observed. Laboratory and field processes were evaluated using a numerical simulation tool coupling an electromagnetic simulator with a thermal reservoir simulator. It was developed and applied for field-scale simulations which indicated up to 38% increase in bitumen production compared to a conventional SAGD results.

Despite considerable progress in experimental and pilot testing, so far the mathematical description of RF-based process has been reduced to simplified and cumbersome in use (except for analytical models) the so-called Bouguer-Lambert-Beer (BLB) law [11,12,13]. Formally, its application is restricted to short-time preheating under the boiling-point temperature, i.e. without phase transition, or other situations where strong assumptions on fluids distribution are valid [14,15]. The connate water evaporation and steam circulation chamber development puts definitely a limit on use of the BLB law in numerical models, and requires solution of the Maxwell equations. The heating power distribution depends mainly on water saturation field around the EM source. So the shape of the water evaporation front (embracing the reservoir region with zero liquid water content) and the water distribution just outside it are particularly important in simulations. This is true especially in case when the EM heating power field overlaps the bitumen-saturated zone and contributes directly to heating of flow region. Both factors are coupled, time-dependent and should be modeled numerically.

As it seemed impossible to find out a dedicated reservoir simulator offering the EM field computations, the simulator coupling model has been developed in our research team (Torres et al. [16]). It launches CMG STARS simulator [17] together with COMSOL electromagnetic (RF) module [18], initializes and controls the data exchange between them and the solutions obtained in both simulators. The main advantage of our coupling code (called EMIR) is that multiphase flow and EM field calculations are done on different temporal and space grids which are independently adapted to their specific solutions. The coupling idea realized in EMIR makes possible to directly model the distribution of EMH power coupled with fluids dynamics (mainly, water) and based on instantaneous and precise electromagnetic computations. The well configuration similar to those used

for SAGD and recently proposed by Kasevich [19] for the EMH was considered.

Making use of EMIR the bitumen recovery under EMH conditions has been modeled in 2D. The main objectives were (1) to quantify the influence of the heating zone and the fluid flow geometry and dynamics on instantaneous and cumulative production; (2) to analyze the thermal efficiency, recovery coefficient and energy-to-oil ratio at different EM field characteristics applied, however, for the same reservoir conditions. Although used for comparison the modeling of the LFH is not concerned in the current work.

The demonstrated potential of the EMH is sufficient to make conclusion in favor of its future applications for real heavy oil reservoir conditions.

Physical background of EMH driven bitumen production

Multicomponent multiphase heat and mass transfer strongly coupled with the EM loss (i.e. heating power) field constitutes a general framework of the recovery method. Consider now general behavior of both physical phenomena and their coupling at reservoir conditions. This will help us to better understand key features of interaction between them and some key parameters of the process model.

Remind that a mechanism of EM energy conversion to heat exists at practically all field frequencies but it is not always efficient, for example, because of medium properties variation with frequency (cf. Vermeulen and Chute [7]). Moreover, the electromagnetic field is strongly coupled to the heat and mass transfer so that preheating and production schemes should be consistent with possible variation of the power field.

EM power field

Up to now the major part of theoretical and numerical models has been based on strong simplifications of EM field equations used for the RFH source description. The great advantage of such a model is its simplicity which helps to gain a conceptual knowledge via order of magnitude estimations at reasonable computational expenses. A typical example is the use of conventional constitutive relation for the RFH source, the so-called Bouguer-Lambert-Beer (BLB) law which, strictly speaking, can be applied to a limited number of practically valuable cases. Other models are required, for instance, to evaluate and optimize the in-situ performance of EM energy source or to estimate the impact of water redistribution on RFH driven oil recovery. Let's consider few examples of EM power field computations.

Three power fields presented in Figure 4 corresponds all to approximately the same cumulative energy generated for the same reservoir initial conditions and properties (Tables 1,2). The connate water redistribution is mainly due to evaporation because the water mobility remains limited. Top and middle rows of figures (4a,d and 4b,e) illustrate different reservoir thickness cases (22m vs. 42m). It can be easily seen that power field is sensitive to distribution of water in reservoir, becoming stronger in water filled zones. The water saturation fields are slightly different because the steam chamber faced cap rock sooner in thinner reservoir and the water banks are wider due to heat loss to and steam condensation near cap rock. Hereinafter arrows show

direction and amplitude of oil local velocity The bottom figures (4c,f) illustrate the case with water co-injection at low flowrate. This case can be characterized like in-situ steam generation as the power field is confined inside steam chamber far from bitumen flow regions. This is the only shown case where power field does not overlap the heated bitumen flow.

The dominating mechanism of EM energy conversion to heat depends on medium properties; usually few of the related phenomena are mentioned in literature. For instance, in case of the low-frequency electric heating (LFH) it is the Joule effect (for some details of the LFH see Harvey et al. [20], Hiebert et al. [21]); the high-frequency or microwave heating (HFH, e.g. [6]) results from the frictional effect of polar molecules (such as, for instance, water molecule) which oscillate in applied EM field. The typical frequency range for the HFH is $1-10^3$ MHz. Finally, the so-called inductive heating (IH, cf. [2]) is a direct consequence of sporadic Foucault (eddy) electric current (the Joule effect), and is frequency-dependent in this case. The IH takes place at frequencies $10^{-3}-1$ MHz and is considered by some authors as a composite effect, since it may take advantage of the Joule effect (if the water remains in liquid state), and of dielectric heating after water evaporation [8]. One of principle reasons why this method is distinguished from the other RFH methods is also a special technique of field applicator (like for instance, the Litz cable) which minimizes the transmission lines losses.

Mathematically speaking, the system of Maxwell equations (e.g. [13]) offer the generalized description of EM phenomena including that part of the field power which is based on effective electric conductivity whatever be the applied EM field frequency and underlying physical mechanisms (see also Appendix). Common mathematical nature of phenomena under consideration explains similar features in the EM field distributions. Mention, for instance, the nearly singular field close to the source: its decay depends on both the problem geometry and the field frequency. Another common point is that in practice the EMH is efficient only if some "critical" amount of connate water is present initially in a reservoir. It means that the reservoir water electric properties make the methods applicable (or not) for given initial conditions. If in case of the LFH the reservoir water has to be always in liquid state around electrodes, for higher frequencies the EM waves propagate (without significant absorption) through a dry porous medium. So like in case of LFH there is no heat release in a dry (liquid water free) medium.

Although the heating mechanism changes with applied field frequency the power distribution follows the same dependency as far as reservoir properties remains the same (see Appendix A). At constant fluid saturations the dimensionless effective size of the heating zone (i.e. the energy absorption length, equation A-5) remains unchanged, $k_0\ell=const$.

The resulting expression for effective electrical conductivity comprises two terms which take into account aforementioned heating mechanisms (equation A-2): the conductivity of moving free electrical charges under the action of electrical field (electrical conductivity, σ) and the term representing the molecular rotational movement and proportional to medium electric permittivity, ε_r. Both effects depend generally on a porous medium type and water content. Recently it was demonstrated that the LFH process

can be controlled via circulation of brine with given electrical properties in near-electrode region [22]. During the HF process the similar conditions of a "remote" heating occur naturally after connate water evaporation in the vicinity of the EM field applicator as there is almost no more EM energy loss inside this "dry" part of the steam chamber (see Figure 4a,b).

Two important features of reservoir EM model might be but were not taken into account in our work. They are: (1) a particular design dependent EM field around the applicator and (2) the field interaction with reservoir which will depend of instantaneous reservoir properties. Both aspects should be a subject of certain optimization during RFH (see [9]).

Heat and mass transfer during RFH

The model of temperature field dynamics comprises the volumetric EM heating source which maintains the conductive and convective heat transfer with a phase transition, influences the pressure and flow distribution, and drives the fluid and heat production. Among other mechanisms the conduction heat transfer is far from being negligible in any of EMH-based process. This mechanism helps to diminish the temperature difference inside the reservoir, on one hand, and may underlie a thermal recovery process, on the other, with energy injection done without injecting a fluid. Recently Bogdanov et al. [22] showed that it may be more efficient that EMH during preheating period.

The advantages of the RFH methods include the aforementioned "remote" heating outside a water-free hot reservoir region (a steam chamber) around an EM field applicator. The reservoir water evaporation makes gravity drainage an important production mechanism, accelerates the energy exchange between heated and cold parts of reservoir and increases locally the pressure and the temperature in reservoir. In-situ steam generation via RFH relates directly the EM methods to SAGD and demonstrates that these methods can be potentially efficient, powerful and applicable for a wide range of reservoir conditions.

One of promising cases of such an application is considered in this paper. Unlike SAGD the RFH driven bitumen production can be done via reservoir connate water evaporation and its circulation over the steam chamber. This is quantitatively different from usual SAGD operational framework. To show this it is probably enough to estimate the SOR of such a process which is SOR=S_{wi} $(\eta S_{oi})^{-1}$ (in m3/m3) (the nomenclature is given at the end of paper). Note that SOR is inversely proportional to η and in particular, SOR=1m3/m3 if the recovery factor is S_{wi}/S_{oi}, i.e. approximately 0.25 (cf. Table 1).

However in practice the use of the RFH may be more expensive and a separate preliminary study is recommended (cf. Vermeulen and McGee [23]). One weak point of the method stems from its advantage: without fluid injection the pressure inside steam chamber is restricted by the initial reservoir pressure which obviously limits the temperature there.

Another difference between SAGD and RFH is that a typical SAGD steam chamber contains some amount of water which is not everywhere mobile but is everywhere liquid. At RFH a "dry" (liquid water free) steam chamber appears and expands around the EM field applicator. Inside this chamber $S_w \approx 0$ and hence, there is no more heating. Therefore the EM field can access and heat the remote reservoir volume and provide finally more efficient bitumen production. Due to high ratio of steam to liquid water specific volume the size of the "dry" chamber is relatively small compared to total steam chamber size, $L_d < L_s$ (cf. Figure 4e). It is clear that if the "dry" chamber remains isolated from bitumen saturated region (BS) or, more precisely, there is no influence of its configuration on heat transfer to BS, the RFH production conditions are rather close to those of SAGD. Then the major difference is in a way the steam is delivered to reservoir in these two cases.

More interesting configuration occurs when the EM power field overlaps the BS region providing additional heating of bitumen and as a result more efficient production. Obviously, in this case the effective length of heating (equation A-5) should meet the overlap condition: $L_d(t)+\ell(t)>L_s(t)$. Note that for short time period ($L_{s,d} \to 0$) this condition is always fulfilled which means that RFH application may be advantageous for this limited time, at least.

Usually, two periods can be distinguished for each EM-driven bitumen recovery, namely, preheating and production (Sresty et al. [6]). Physically speaking, the principal objective of preheating is to deliver a necessary amount of energy for making production possible. At this stage the connectivity between wells should first be provided mainly as a result of the local temperature rise. Different preheating scenarios can be envisaged subject to particular reservoir conditions and production limits. The perfect, i.e. fast and homogeneous, preheating mentioned elsewhere (cf. [1]) can be possible if additional heat transfer mechanisms are used to manage, in particular, the "hot spots" effect etc.

RFH modeling approach

Multiphysical framework

Using the BLB law, i.e. a simplified EMH power formulation, it is possible to develop useful analytical solutions providing feasible estimates and predictions (cf. Carrizales et al. [3]). Other model is necessary to work with field-scale applications and we have chosen a multiphysical coupling strategy. A project of code capable to launch and control the data exchange between the reservoir simulator and COMSOL *Multiphysics*, has been worked out. Within this framework the multiphysics simulator proved to be a good choice as (1) it is well-suited for coupling by definition and (2) different physics and their combinations are available.

The recently developed and tested in-house code did carry out coupled simulation of the EMH applications for bitumen reservoir. This code follows a loose explicit coupling algorithm which implies that the thermal multicomponent flow and the EM field models are solved sequentially with different solvers [16]. A finite-volume reservoir simulator solves its usual energy and multicomponent transport problem while a finite-element electromagnetic simulator provides the instantaneous heating power distribution (see Appendix A). Both solutions undergo certain predefined transformations during data exchange. For example, the interpolation of necessary composition- and temperature-dependent reservoir properties is done using coupling code utilities and the results are stored on the finite element grid. Furthermore, the finite element computations of the heating power density are followed by the spatial integration of the power over each block of the reservoir model grid.

Each simulator works independently and solves separately the system of equations of different type: transient non-linear parabolic or parabolic-elliptic system of multiphase transport and stationary hyperbolic system of EM field equations. Now it seems quite natural that they work with different grids using different solvers. Moreover, the computational regions for coupled problems are not obligatory coinciding so that a special mapping is used for the common subdomain specification. Parallel computations and adaptive meshing have been much involved in our computations. The test problem solutions, comparison to known reference solutions, choice of adequate numerical parameters like grid block sizes, coupling frequency *etc.* can be found elsewhere [16].

Problem formulation and parameters description

The EMH driven bitumen production begins with an EM field applicator (electrode, cable, antenna etc.) installation directly in a special well. Depending on particular deposit characteristics this well may be vertical or horizontal which changes somewhat in the distribution of the heating power in the reservoir but doesn't change much the principal recovery features, mechanisms and duration. The 2D Cartesian geometry has been used here to model the bitumen production (Figure 1) so that hereinafter the problem will be referred to as 2DC. The chosen well pattern is similar to well-known SAGD pair of horizontal wells, the production being done via bottom well (cf. Kasevich [19]). In this configuration the EM field "injection" directly replaces the conventional steam injection, which constitutes the major difference between two methods. From the other side, the gravity drainage remains the most reliable oil production mechanism in both cases. The distance separating two horizontal wells may do the initial stage longer (or shorter) and technically more (or less) involved. The initial reservoir conditions and geometrical parameters of the cases under consideration are given in Table 1. The physical properties of solid and fluids are presented in Table 2 and in Figure 2.

Two rock layers (in top and bottom of the reservoir) were added to compute more precisely the EM field and power distribution, and also the heat loss from reservoir. Though different options are available to model the EM field propagation in COMSOL, the harmonic field equations (see Appendix A) seem most appropriate for our study. Field continuity conditions on all internal boundaries including those between the reservoir and burdens, and scattering conditions on all external boundaries of the model region were used. The problem geometry reduced the intersection between reservoir and applicator to a circle. Although possible we didn't model here the EM interaction between applicator and reservoir and the transmission lines parameters. Some details of such a modeling can be found elsewhere (Godard and Rey-Bethbeder [24]). It follows that by total cumulative energy in our results we mean the total cumulative in-situ generated heat, i.e. the part of the EM energy converted to heat in the reservoir. Transmission line loss and global EM applicator efficiency are not considered in our model.

Mention in passing that the grid shown in Figure 1a is that of CMG simulator; the finite-element adaptive grid can be much finer locally, for instance, along the steam chamber boundary or close to well (Figure 1b). Taking advantage of the improved description of the EM power field, our objective is to investigate the production rate and its efficiency dynamics at different field frequencies, power and operational conditions. It will be shown in particular that independently of frequency and power of the field, the heated oil can be produced by gravity drainage enhanced by gas or steam injection at relatively low rate. The study cases included the RFH at different EM field frequency (from 0.1 to 4 MHz) and the production period comprising well-pressure operations aimed to replace the produced volume and to enhance the oil recovery.

This work can be seen as a direct continuation of more recent one dedicated to the EMH method and reported the first results [25]. To set a physically feasible reference to the EMH cases under consideration, the recently published results on the bitumen recovery by SAGD and pure conductive reservoir heating are used below.

Efficiency of bitumen recovery

One of the advantages of RFH methods is their ability to adapt the heating to different local reservoir conditions (e.g. Carrizales et al. [3]) and due to this, a possible efficient control of process. Theoretically, the more uniform is the temperature in reservoir, the better. This idea has been developed and tested, for instance, by IITRI (Sresty et al. [6]). However, in practice it may be not always true. Unlike the LFH where the water evaporation has to be avoided, it may be acceptable and even desirable for the heating at higher frequencies. The fast local evaporation of connate water may lead to a net improvement of heating efficiency due to the EM field propagation through "dry" chamber without considerable attenuation which results in deeper penetration of the RFH power, and also to the steam penetration outside the chamber. As to production it will be enhanced by gravity drainage related to steam chamber development.

Production mechanisms

Unlike the SAGD where the temperature in the steam chamber varies with injection pressure, the RFH driven production can hardly be done at temperature exceeding the saturated steam temperature at initial reservoir pressure. The viscosity of bitumen at this temperature is much lower than initial one but remains considerably higher than viscosity of reservoir water (20 to 120 cp depending on production temperature, Figure 2). The principal production mechanisms are related to presence of a gas phase (water evaporation, gas injection …) and include "countercurrent" oil flow into EM well in the direction opposite to the steam chamber expansion (Carrizales et al [14], Soliman [15]) and, obviously, the gravity drainage.

It can be shown that for the countercurrent production scheme with water evaporation the oil recovery may be estimated within 30%. Starting with the development of steam chamber, the fluids separation by gravity drainage can result in recovery of all bitumen but immobile (critical) fraction. The necessary condition for this is the generation (or injection) of sufficient amount of gas in the reservoir. It is worth to note that the water condensation during RFH may provoke a strong thermal convection of fluids including heated hydrocarbons which makes production poor. Mention also that at equivalent cumulative energy generated in reservoir the gravity drainage is more efficient in case with

smaller heat loss and more uniform temperature field in reservoir as is explained below.

In-situ power distribution

As for any method based on in-situ heating (SAGD, CSS, in-situ combustion etc.) the EMH results depend finally on how efficiently the thermal energy is used in reservoir. The efficiency will depend on a fraction of total energy generated in the reservoir which is used to heat the bitumen-saturated volume. The general indicator of the production efficiency may be so-called energy-to-oil ratio (EOR, J/m^3). The low EOR values indicate more efficient recovery process with lower production of steam and hot water and/or lower heat loss as a result of reduced thermal exchange with burdens.

As it has been stated above, similar to SAGD the gravity drainage is principal mechanism of bitumen production in our case. By analogy we may suppose that one of the important RFH features is the temperature distribution across the flow in BS region just outside the steam chamber (cf. Butler [26]). This temperature profile shows in particular the energy used to directly heat the produced bitumen. The main difference between SAGD and RFH is the presence of heating power field which may influence the temperature in BS region. Therefore it makes sense to understand at which conditions the heating power field overlaps the gravity driven flow region. To do this it is enough to juxtapose the flow configuration with the power and/or the temperature field. One configuration appeared at doubled EM power are presented in Figure 5. The power has been doubled after 400 days and given far better recovery at equivalent generated energy (cf. oil saturations in Figure 5c,f).

Increase in EM power results in enhanced direct heating of BS reservoir volume and by this, improved recovery efficiency.

Let's consider now the role and the characteristics of the first RFH stage – the preheating.

Preheating

It could be expected that the uniform and fast temperature growth is a main objective of the preheating stage. There is no obvious contradiction between the quality (uniform) and the rate (fast) of heating as the "uniform" power field can be generated at relatively low frequency while the "fast" heating can be done at higher power. Remind in passing that pure "conductive" heating (for example, from a well which is equipped by an electrically heated load) remains most efficient at early time.

Surprisingly, the modeling results demonstrate the advantage of more concentrated or narrow heating zone at early time. The results for different power field sources and configurations, namely, a singular "conductive" preheating from the horizontal well (1), more deep EM heating which remains, however, relatively narrow due to significant reservoir electric conductivity (2) (see Figure 3, Table 1) and finally, power field with greater effective heating length (ℓ) at negligible reservoir conductivity (3), are depicted in Figure 6. The curves of bitumen production versus cumulative generated energy show clearly the difference at early time between (1) and (2) – Figure 6a and between (2) and (3) – Figure 6c. More compact power field creates faster the steam chamber and enhances heat transfer between the wells.

Heat exchange with burdens

Under conditions of thermal flow driven by gravity the role of over- and underburden is different. The overburden puts a barrier to steam vertical convection, turns it horizontally and as a result accumulates the thermal energy faster than its lower counterpart. The heat exchange (heat loss) at reservoir top induces partial condensation of the steam and descending flow of hot water. This sweeps out, firstly, the heated bitumen from the reservoir top (Figure 5c,f) and increases, secondly, the generated power here (Figure 4b). Increased power dries gradually the liquid water and maintains the equilibrium water saturation near the top.

The underburden contacts the reservoir with descending hot liquids; the heat exchange here is normally less intensive than at top. To quantify the role of burdens let's compare the production (or production efficiency) curves for the cases H=22m and 42m (Figure 6a, 7b). The difference appears and grows after approximately 900 days of the process when the ascending steam flow faces the top rock. The vertical steam flow deviation and increased heat loss reduce the production efficiency in case of smaller H.

Note also that heat loss becomes more important at lower RFH power because of increasing time of the process in a whole and of the heat exchange in particular. It means that higher power (smaller time and heat loss) can be used more efficiently in similar conditions.

Frequency and total power impact on production

These two parameters of the EMH driven recovery are important both from the physical viewpoint and as possible means to control the process from the surface. It should be noted that the problem of optimal production conditions in terms of power and field frequency remains still an open issue. This problem involves some design aspects of an EM energy applicator (antenna, cable, electrode) and the dynamics of its interaction with reservoir which follows the in-situ fluids distribution. The proper modeling of this interaction is one more argument in favor of adequate electromagnetic field model to use in computations of such a kind.

As far as transmission lines loss and interaction of the applicator with reservoir are not concerned in current paper, the frequency (together with reservoir electric properties) defines probably only one important physical factor: the effective length of power penetration or length of EM heating (ℓ^{-1}=2 Re(k), equations A-5, A-6, Fanchi [13]). The permittivity of water is generally a frequency dependent value (Vermeulen and Chute [7]) so the relatively simple dependency between ℓ and ω used in current paper may not be applicable for all real cases. At small heating length the conductive heat transfer to BS region dominates while at greater length (hereinafter equivalent to lower frequency, Figure 3) it is easier to provide the EM power for *direct* heating of the bitumen flowing just outside of the steam chamber.

The effect of increasing power on production can be explained in the similar way, i.e. the power growth itself and following faster expansion of the DC may both contribute to the local temperature rise in heated bitumen flow region.

The considerations above help to understand at which particular conditions the effect of power and/or frequency variation can be reached. Let's analyze two cases of different reservoir water electric conductivity which correspond to

relatively high and low (here, negligible) salinity (σ_w =1 and σ_w =0 S/m, respectively, see Table 1 and equations A-2, A-4). The power distribution in these two cases at initial reservoir conditions, frequency ν=0.1 MHz and total power about 1 kW/m are shown in Figure 3b,c. It is clear that the heating power field is significantly wider at low salinity. Using the expression for the effective electric conductivity which include both standard (i.e. frequency independent) and dielectric terms (A-2) it is not difficult to demonstrate that the electric conductivity of reservoir at high salinity dominates ($\sigma_R \gg \omega\varepsilon_r''$). At this limit the shape of power distribution is different because of high medium loss tangent which makes it close to higher frequency field with smaller effective heating length (Figure 3a).

So the principle difference between the power fields at different water conductivity is that at high salinity the field is nearly independent of frequency. Moreover the small heating length makes the recovery efficiency nearly independent on total power generated into reservoir. The bitumen production dynamics demonstrates a small influence of frequency and very limited and short impact of power variation on production (see Figure 6a,b). However, there exists a certain power level when production efficiency becomes far better (Figure 6b,c, curves with power "multiplyer" 2.5 at different frequencies and salinity conditions). It follows that at low enough EOR the recovery process of such a kind can be applicable in a wide range of reservoir conditions.

As it can be easily seen, increasing total power or field frequency reduce the typical time of in-situ temperature rise and of the preheating period in whole. For instance, the production results for higher power depicted in Figure 6b show at least similar process efficiency and hence a potential for the process time reduction. The production enhancement, however, does not mean the increase of ultimate bitumen recovery.

Water co-injection and production pressure variations

The foregoing recovery results have been obtained mainly at gravity drainage taking place inside steam circulation chamber developed and maintained via RFH.

Recently it has been demonstrated that the heavy oil recovery can be enhanced by stable gravity-assisted displacement provided, for instance, by a gas injection from the upper section of an EM well (Wacker et al. [10]). Taking advantage of idea described in [1] the steam injection with moderate rate (which mimics the water injection) at given BHP pressure conditions was tried with double-purpose: to limit the temperature of "hot spots" near the EM field applicator and to enhance the oil production by steam introduced in such a way. The injection of steam with low flowrate (from 0.02 to 0.125 m^3/day in liquid water equivalent) improved considerably the production whatever be the EM field frequency and power (Figure 7a). Like in case of LFH, the water injection at moderate rate seems an effective mean to improve the process efficiency.

Another idea of production enhancement by diminishing gradually the production well pressure has also been realized (cf. Bogdanov et al. [25]). The BHP pressure has been decreasing (at rate about 1.2bar/year) once per year during 5 years. This has led, first, to recovery enhancement and confirmed, second, that combination of the RFH with pressure operations can improve the production rate, the oil recovery factor and hence the global efficiency of the process (Figure 7b). The best EOR reached in our study varies within

5 and 6 GJ/m^3 (at SC), the latter being the reference even for long-time production.

Conclusions

- the EM heating power field and its evolution during bitumen production period may be computed more precisely and efficiently using dedicated simulators and in-house coupling code developed recently;
- our numerical analysis shows that the RFH assisted bitumen recovery is a method with a promising thermal efficiency. The choice of the EM field power and frequency may be different and RFH can be applicable for a wide range of reservoir conditions;
- water electrical properties proved to be very important in the choice of RFH operational conditions;
- the RFH-assisted bitumen production efficiency can be enhanced by low rate water or gas co-injection or production pressure variation

Acknowledgement

Nomenclature

Roman letters

c_0 =	speed of light in empty space, L/t, m/s
h =	distance between electromagnetic and production well, L, m
i =	$(-1)^{1/2}$, n
k_0=	wave number (empty space), 1/L, 1/m
k =	wave number (reservoir), 1/L, 1/m
k_e=	wave number (uniform medium), 1/L, 1/m
ℓ =	energy absorption length, L, m
m =	power parameter in Archie's law, n
t =	time, t, s
E_0=	input electric field, q/t/L, A/m
H=	reservoir thickness, L, m
J=	heating power source term, m/L^{2}t, W/m3
L=	half-distance between well pairs, L, m
S_{oi}=	initial oil saturation, n
S_w=	water saturation, n
S_{wi}=	initial water saturation, n
T=	temperature, T, K
X=	space variable, L, m
Y=	space variable, L, m
Z=	space variable, L, m

Greek letters

β=	lithology parameter in Archie's law, n
ε_0 =	electric constant (free space electric permittivity), q^{2}t/L^{3}m, C/V/m
ε_r =	bulk relative electric permittivity, n
ε_r'=	bulk relative electric permittivity, real part, n
ε_r''=	bulk relative electric permittivity, imaginary part, n
ϑ =	dimensionless reservoir thickness, n
η =	oil recovery factor, n

$\sigma =$ effective reservoir conductivity, q^2t/L^3m, S/m
$\sigma_B =$ electric reservoir conductivity, q^2t/L^3m, S/m
$\sigma_w =$ water phase electric conductivity, q^2t/L^3m, S/m
$\phi =$ porosity, n
$\omega =$ angular EM wave frequency, 1/rad
$\chi =$ dimensionless space variable, n
$\psi =$ dimensionless space variable, n
$\xi =$ dimensionless space variable, n
$K =$ bulk reservoir heat conduction coefficient, mL^2/t^3LT, W/(m K)

References

1. MCGEE, B. C. W., and VERMEULEN, F. E., The Mechanisms of Electrical Heating for the Recovery of Bitumen From Oil Sands, *Journal of Canadian Petroleum Technology, Vol. 46, No. 1, pp. 28-34, 2007.*

2. KOOLMAN, M., HUBER, N., DIEHL, D., and WACKER, B., Electromagnetic Heating Method to Improve Steam Assisted Gravity Drainage, *SPE 117481-MS, paper presented at the International Thermal Operations and Heavy Oil Symposium, 20-23 October 2008, Calgary, Alberta, Canada.*

3. CARRIZALES, M.A., LAKE, L.W., and JOHNS, R.T., Multiphase Fluid Flow Simulation of Heavy Oil Recovery by Electromagnetic Heating, *SPE 129730-MS, paper presented at the 17th SPE Improved Oil Recovery Symposium, 24-28 April 2010, Tulsa, Oklahoma, USA.*

4. DAVLETBAEV, A., KOVALEVA, L. and BABADAGLI, T., Mathematical Modeling and Field Application of Heavy Oil Recovery by Radio-Frequency Electromagnetic Stimulation, *J. Petr. Sci. and Eng., Vol. 78, No. 3-4, pp. 646-653, 2011.*

5. BRIDGES, J.E., SRESTY, G.C., DEV, H., In Situ RF Heating for Oil Sand and Heavy-Oil Deposits, *IIT Research Institute, Chicago, Illinois, 11 pp., 1985.*

6. SRESTY, G.C., DEV, H., SNOW, R.H., and BRIDGES, J.E., Recovery of Bitumen from Tar Sand Deposits With The Radio Frequency Process. *SPERE, Vol. 1, No. 1, pp. 85-94, 1986.*

7. VERMEULEN, F.E. and CHUTE, F.S., Electromagnetic Techniques in the In-Situ Recovery of Heavy Oils, *Journal of Microwave Power, Vol. 18, No. 1, pp. 15-28, 1983.*

8. MCPHERSON, R.G., CHUTE, F.S., and VERMEULEN, F.E., Recovery of Athabasca Bitumen With the Electromagnetic Flood (EMF) Process, *Journal of Canadian Petroleum Technology, Vol. 24, No. 1, pp. 44-51,* 1985.

9. KASEVICH, R.S., S.L. PRICE, D.L. FAUST, and FONTAINE, M.F., Pilot Testing of a Radio Frequency Heating System for Enhanced Oil Recovery from Diatomaceous Earth, *SPE 28619, SPE 69th Annual Technical Conference and Exhibition held in New Orleans, LA, 25-28 September 1994.*

10. WACKER, B., KARMEILEOPARDUS, D., TRAUTMANN, B., HELGET, A., and TORLAK, M., Electromagnetic Heating for In-Situ Production of Heavy Oil and Bitumen Reservoirs, *Canadian Unconventional Resources Conference, Calgary, 15-17 November 2011.*

11. BOUGUER, P., Essai d'optique sur la gradation de la lumière, *Paris: Claude Jombert, 1729.*

12. ABERNETHY, E.R., Production increase of heavy oils by electromagnetic heating, *Journal of Canadian Petroleum Technology, Vol. 15, No. 3, pp. 91-97, 1976.*

13. FANCHI, J.R., Feasibility of Near-Wellbore Heating by Electromagnetic Irradiation, *SPE Advanced Technology Series, Vol. 1, No. 2, pp. 161-169, 1993.*

14. CARRIZALES, M.A., LAKE, L.W., and JOHNS, R.T., Production Improvement of Heavy-Oil Recovery by Using Electromagnetic Heating, *SPE 115723 paper at the 2008 SPE Annual Technical Conference and Exhibition held in Denver, Colorado, USA, 21–24 September 2008.*

15. SOLIMAN, M.Y., Approximate Solutions for Flow of Oil, Heated Using Microwaves, *Journal of Petroleum Science and Engineering, Vol. 18, No. 1/2, pp. 93-100, 1997.*

16. TORRES, J.A, BOGDANOV, I.I., DABIR, V., and KAMP, A.M., Analysis of Coupled and Fully Integrated Models for Low-Frequency Electrical Heating Assisted Heavy Oil Recovery, *Proceedings of the 12th European Conference on Mathematics in Oil Recovery (ECMOR XII), Oxford, United Kingdom, 2010.*

17. CMG STARS User's guide, 2010.

18. COMSOL Multiphysics 2008. RF Module User's Guide, Version 3.5ª, *November 2008.*

19. KASEVICH, R.S., Method and apparatus for in-situ radiofrequency assisted gravity drainage of oil (RAGD), *US Patent No 7,441,597, 2008.*

20. HARVEY, A. H., ARNOLD M.D. and EL-FEKY, S.A., Selective Electric Reservoir Heating, *Journal of*

Canadian Petroleum Technology, Vol. 18, No. 3, pp. 47-57, 1979.

21. HIEBERT, A.D., VERMEULEN, F.E., CHUTE, F.S. and CAPJACK, C.E., Numerical Simulation Results for The Electrical Heating of Athabasca Oil-Sand Formations, *SPERE, Vol. 1, No. 1, pp. 76-84, 1986.*

22. BOGDANOV, I.I., TORRES, J.A., AKHLAGHI, H.A., KAMP, A.M., The Influence of Salt Concentration in Injected Water on Low-Frequency Electrical-Heating-Assisted Bitumen Recovery, *SPE Journal, Vol. 16, No. 3, pp. 548-558, 2011.*

23. VERMEULEN, F., and MCGEE, B.C.W., In Situ Electromagnetic Heating for Hydrocarbon Recovery and Environmental Remediation, *Journal of Canadian Petroleum Technology, Vol. 39, No. 8, pp. 24-28, 2000.*

24. GODARD, A., and REY-BETHBEDER, F., Radio Frequency Heating, Oil Sand Recovery Improvement, *SPE 150561-PP, paper presented at the Heavy Oil Conference & Exhibition, Kuwait City, Kuwait, 12-14 December, 2011.*

25. BOGDANOV, I., TORRES, J.A., KAMP, A., CORRE, B., Comparative Analysis of Electromagnetic Methods for Heavy Oil Recovery, *SPE 150550-PP, paper presented at the Heavy Oil Conference & Exhibition, Kuwait City, Kuwait, 12-14 December, 2011.*

26. BUTLER, R. M., Thermal Recovery of Oil and Bitumen, *Prentice-Hall, Inc., Calgary, Alberta, 1998.*

Appendix A (Heading Level 1)

EM heating power density

The coupling term between the EM field and multiphase flow equations is the heating source which generally reads as

$$J = \mathrm{Re}\left(\sigma|E|^2\right) \quad\text{..(A-1)}$$

Here J is the heating power density; σ the effective bulk electrical conductivity and E the (complex) electric field. The calculation of the effective electrical conductivity of reservoir is an important point in this study since it depends generally on (multiphase) fluid composition, frequency, temperature etc. This is a complex value taking into account conductive and dielectric phenomena and containing typically two terms:

$$\sigma = \sigma_B + i\omega\varepsilon_0\varepsilon_r, \quad\text{..(A-2)}$$

where σ_B is the reservoir conductivity given conventionally by Archie's law (see below), ω angular EM wave frequency,

ε_0 electric constant (void space electrical permittivity), ε_r bulk relative electric permittivity for which linear mixing law has been chosen. This means that both components of complex permittivity ε_r,

$$\varepsilon_r = \varepsilon_r' - i\varepsilon_r'' \quad\text{..(A-3)}$$

are proportional to volume fractions of constituants (*e.g.* fluid saturations). Here ε_r', ε_r'' are real and imaginary part of reservoir relative permittivity and $i=(-1)^{1/2}$. The standard formulation of Archie's law (without temperature dependency factor) is used in current work which reads as

$$\sigma_B = \beta\sigma_w\phi^m S_w^n \quad\text{..(A-4)}$$

Here σ_w is the liquid water electrical conductivity at reference conditions, ϕ porosity, S_w water saturation, β, m and n the constant parameters, β being reciprocal to tortuosity factor. So the heating source J is solution dependent and a strong coupling occurs between electrical and thermal flow phenomena.

There is at least one more physical factor which should be specified here. It is so-called energy absorption length which characterizes the heating power attenuation in a uniform medium (cf. [13]) and may be written as

$$\ell = \left\{ \sqrt{2}k_0 \cdot \left[\left(\varepsilon_r'^2 + \left(\varepsilon_r'' + \frac{\sigma_B}{\varepsilon_0\omega} \right)^2 \right)^{1/2} - 1 \right]^{1/2} \right\}^{-1} ,\text{........(A-5a)}$$

which gives for non-conducting medium at $|\varepsilon_r|\gg1$,

$$\ell \approx \left(\sqrt{2}k_e\right)^{-1} \quad\text{..(A-5b)}$$

Here $k_e=k_0|\varepsilon_r|^{1/2}$, $k_0=\omega/c_0$ is the EM wave number and c_0 speed of light, both taken in a free space, ε_r is defined in A-3. Remind that without loss of generality the reservoir magnetic permeability can be taken equal 1. The variation of the heating length with frequency at different reservoir water salinities (see Table 1) is presented in Figure 3a together with corresponding examples of power field (Figure 3b,c).

It should be mentioned that, strictly speaking, the effective length ℓ is defined for a uniform medium. Despite this it is referred to as typical EM heating size throughout the paper for cases where reservoir electrical properties are not at all uniform. It's done for illustrative purpose only and this value has never been used in calculations.

EM field model

Harmonic EM field formulation has been used for computation of power density term given by (A-1). The electric field was determined either from resulting equation for the harmonic field which reads as

$$\nabla\times\nabla\times\mathbf{E} + k^2\mathbf{E} = 0 \quad\text{..(A-6)}$$

or provided magnetic field problem solution, it can be determined directly from Faraday's law equation (written for harmonic field):

$$\nabla \times \mathbf{E} = i\omega\,\mathbf{B} \quad\text{...} (A\text{-}7)$$

Here k is the wave (complex) number of EM field propagating in reservoir where the propagation velocity depends on medium electromagnetic properties (such as relative permittivity ε_r and relative magnetic permeability μ_r),

B is magnetic flux density vector. The model accounts for variable physical properties of reservoir including a particular case of a composite-like medium with frontal properties variation like it may often happen at steam circulation chamber evolution.

Note finally that the dimensionless equation A-6 for $\hat{E}(\chi,\psi,\xi)$ where $\hat{E}=E/E_0$, $(\chi,\psi,\xi)=(k_0 X, k_0 Y, k_0 Z)$, shows that dimensionless electric field $\hat{E}$ depends only on electric properties distribution in reservoir, $\varepsilon_r(k_0 X, k_0 Y, k_0 Z)$.

TABLE 1. RESERVOIR CONDITIONS AND MODEL PARAMETERS		
Length	2*100	m
Height	22 / 42	m
Interwell distance	10	m
Porosity	30	p.u.
Permeability	3000	md
Rock volumetric heat capacity	$1.94 \cdot 10^6$	J/m³/°C
Burdens volumetric heat capacity	$2.01 \cdot 10^6$	J/m³/°C
Burdens thermal conductivity	$2.22 \cdot 10^5$	J/m/D
Oil initial viscosity	1000	Pa·s
Injection pressure	$1.16 \cdot 10^6$	Pa
Initial reservoir pressure	10^6	Pa
Initial reservoir temperature	10	°C
Initial water saturation	20.2	%
Initial bulk relative permittivity, imaginary part	0.48	
Initial bulk relative permittivity, real part	7.38	
Initial bulk electric conductivity (high salinity)	0.0087	S/m
Initial bulk electric conductivity (low salinity)	0.0	S/m

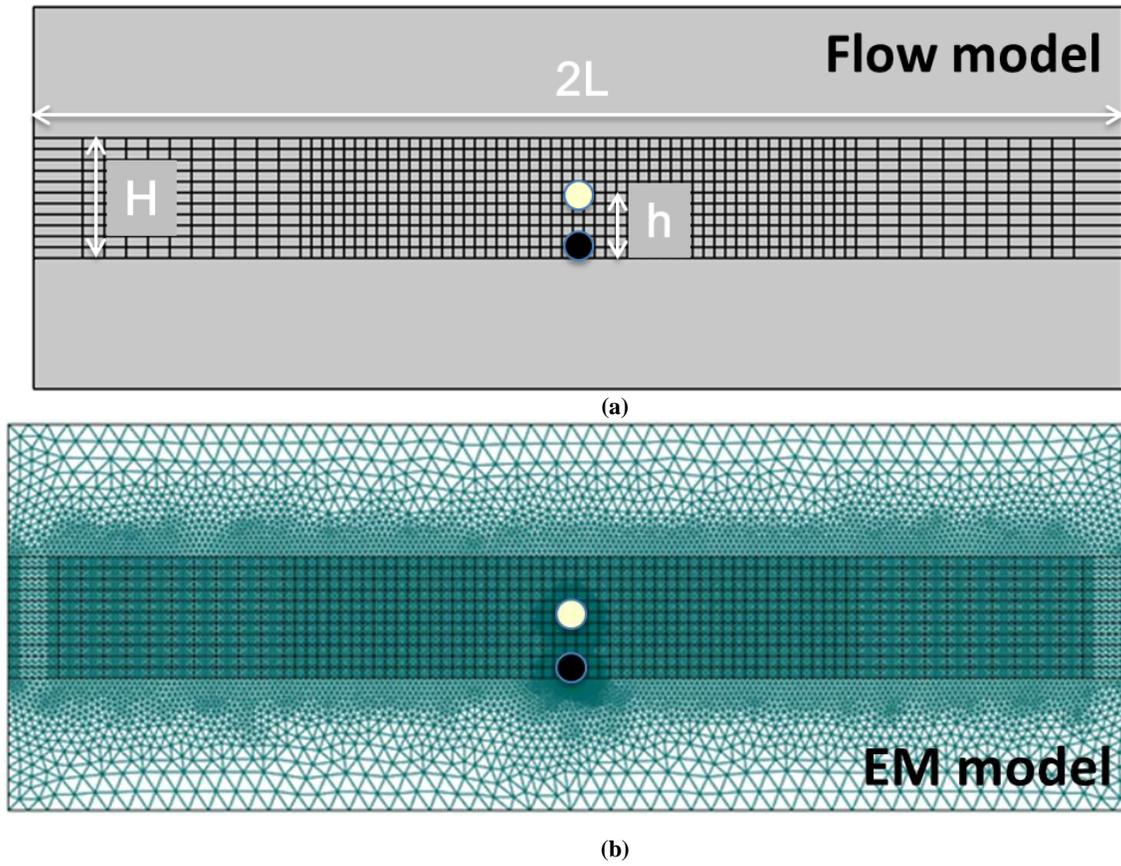| TABLE 2. ROCK AND FLUID PROPERTIES USED BY NUMERICAL MODELS					
Component	Phase	Density, mol/m³	Thermal expansion coefficient, K⁻¹	Compressibility coefficient, kPa⁻¹	Thermal conductivity coefficient, J/m/K/D
Oil	Bitumen	2020	$7.85 \cdot 10^{-4}$	$6.84 \cdot 10^{-7}$	$9.27 \cdot 10^3$
Water	Aqueous/Gas	55490	$7.20 \cdot 10^{-4}$	$5.80 \cdot 10^{-7}$	$5.68 \cdot 10^4$
Rock	Solid	–	–	$7.0 \cdot 10^{-6}$	$6.56 \cdot 10^5$
Methane	Gas	42.5	$8.00 \cdot 10^{-4}$	$5.5 \cdot 10^{-7}$	$4.00 \cdot 10^3$

(a)

(b)

Figure 1. Geometries and grids of coupled models: CMG STARS (a) and COMSOL (b); horizontal EM (○) and production well (●) positions are marked by enlarged symbols.
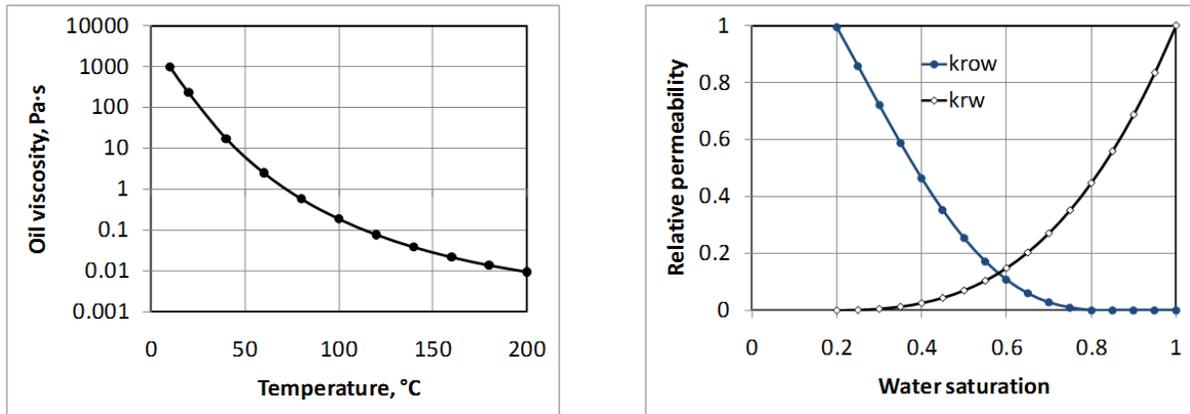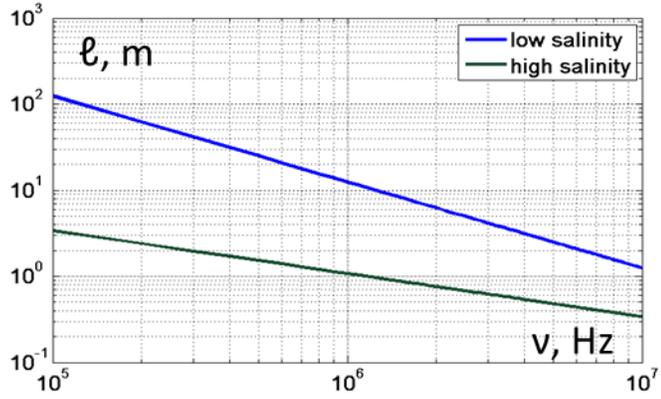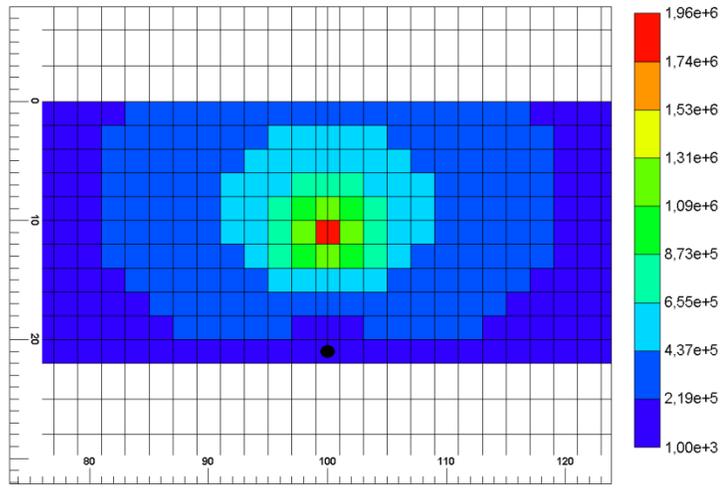

Figure 2. Fluids transport properties: temperature dependent bitumen viscosity (left) and phase relative permeabilities at reservoir conditions (right).
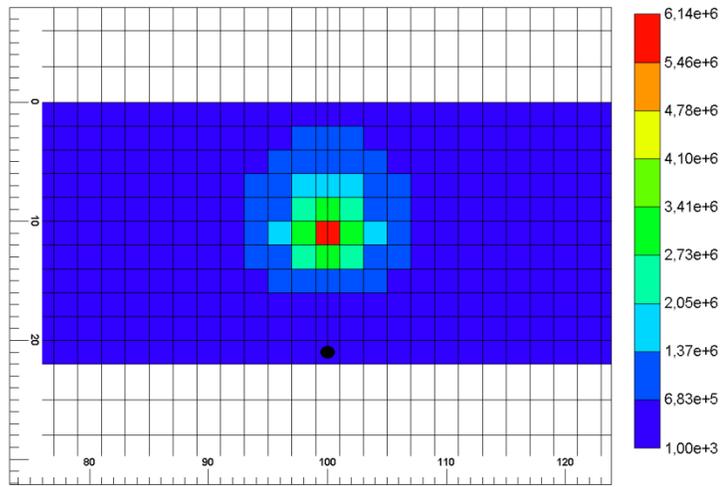
(a)

(b)

(c)

Figure 3. Effective heating length: variation with frequency at low ($\sigma_B=0$) and high salinity according to equation A-5 (a); examples of early preheating power fields at ν=0.1MHz for low (b) and high salinity (c) cases.
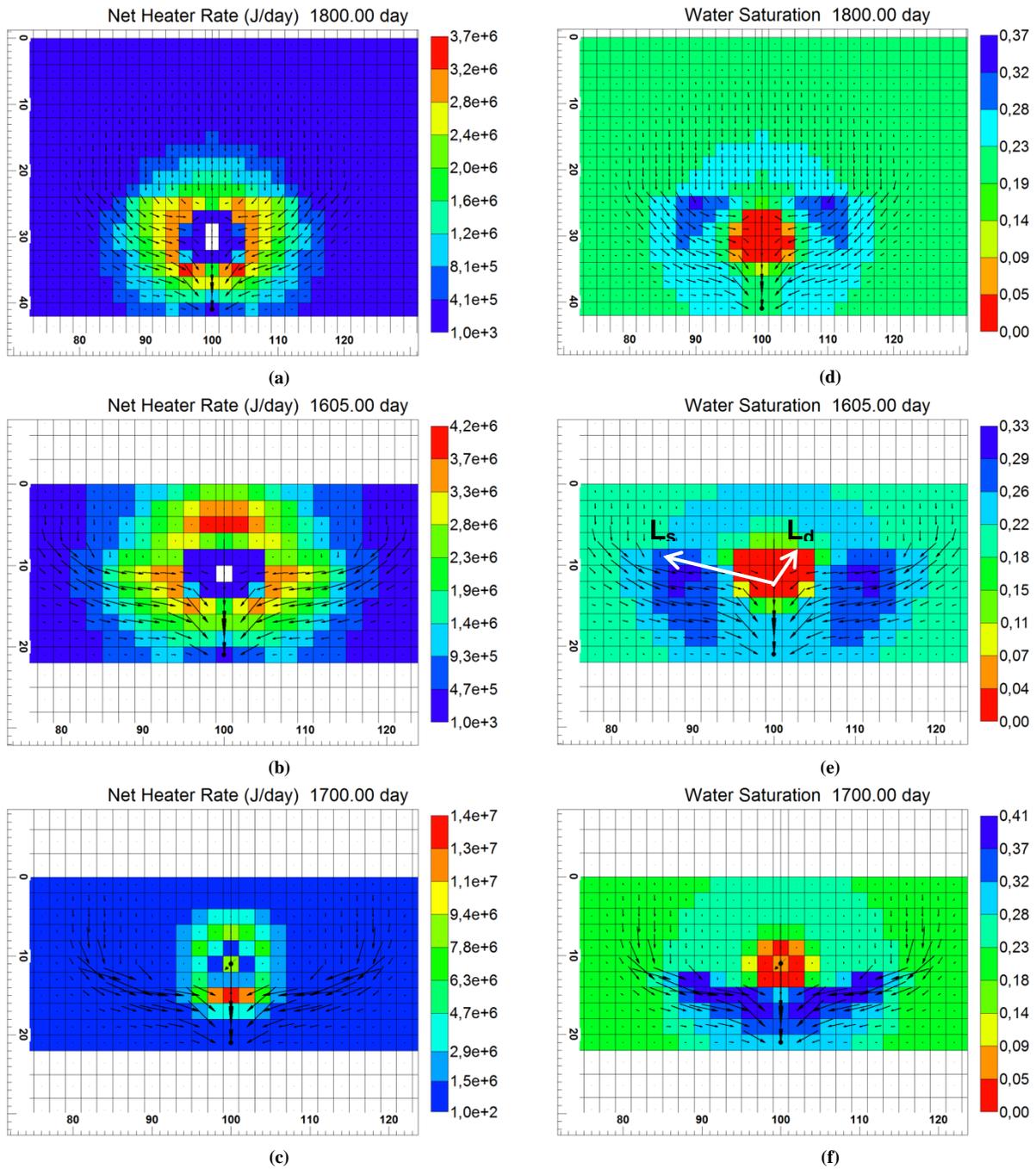
Figure 4. Examples of power (in Joule/day per grid block) and water saturation fields at equivalent total cumulated energy generated: H=42m, ν=0.1MHz (a),(d); H=22m, ν=0.1MHz (b),(e), H=22m, ν=1MHz, water co-injection 0.05 m³/day (c),(f). Arrows show local oil velocity field, direction and magnitude in each grid block.
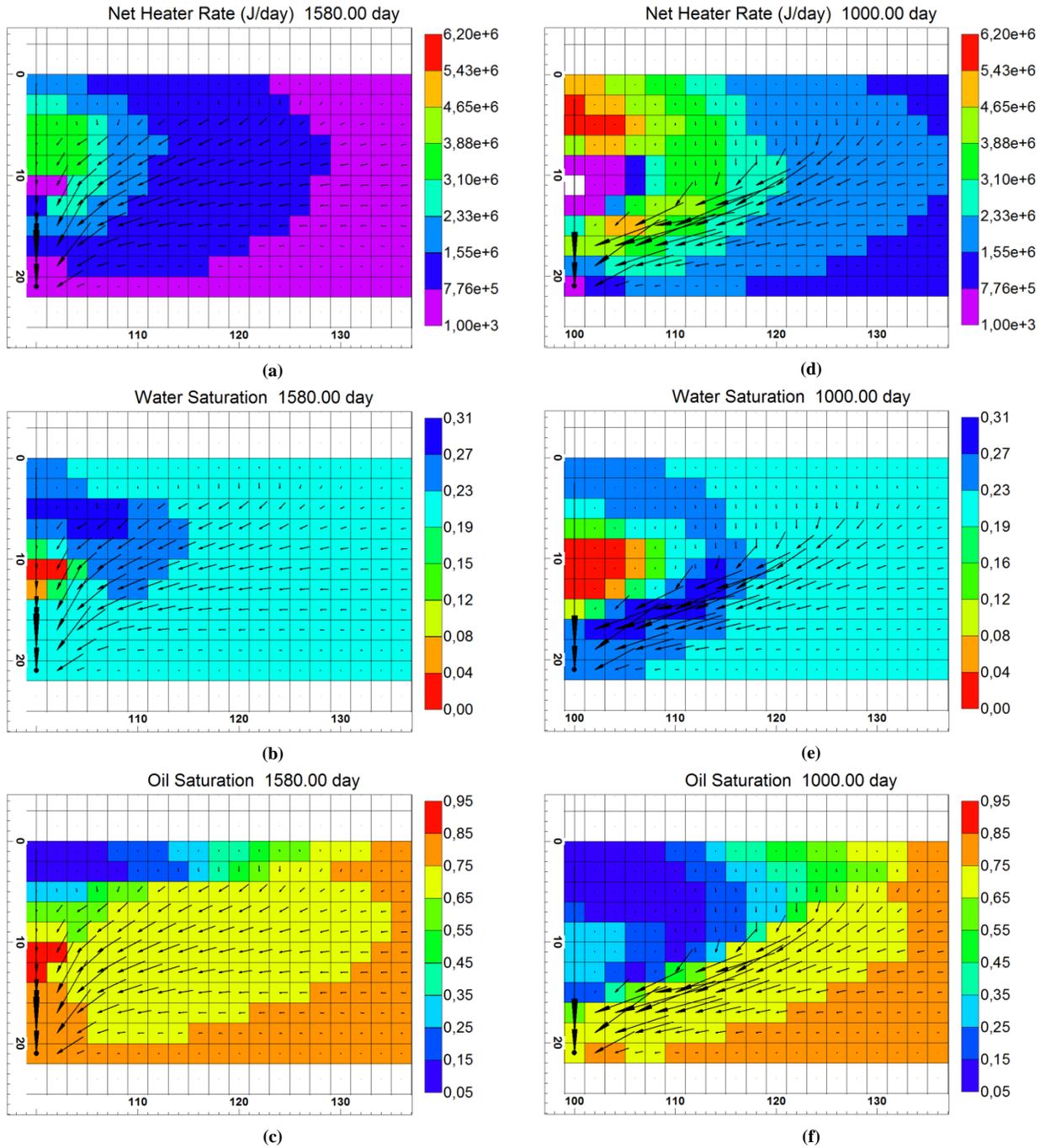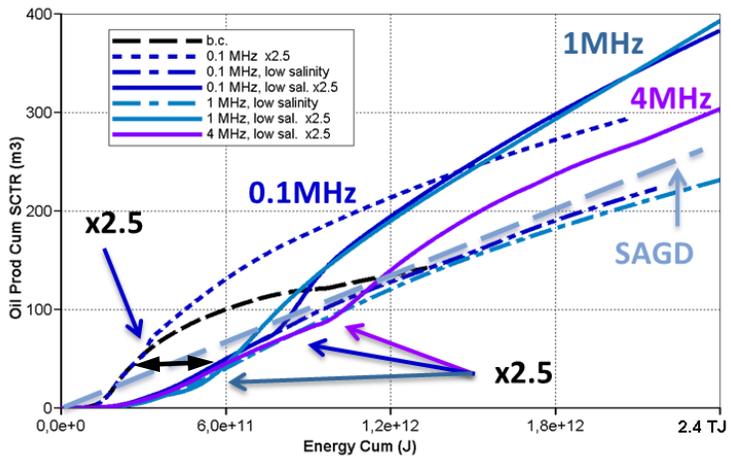
Figure 5. Effect of increased total power at equivalent cumulative energy generated, v=1MHz, low salinity case. Arrows show direction and magnitude of local bitumen velocity in each grid block.
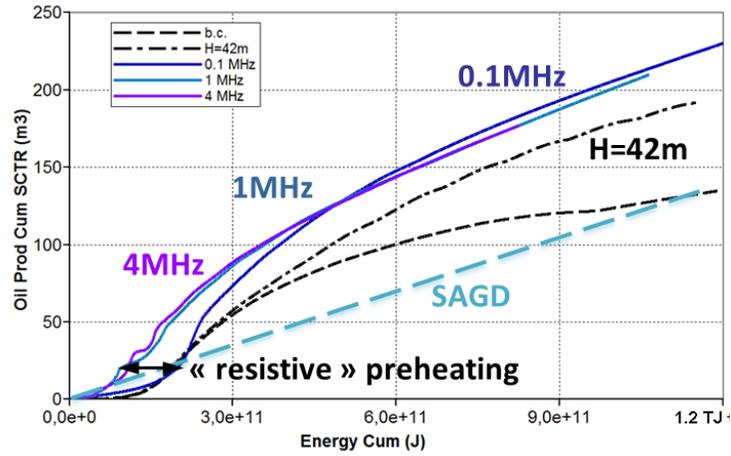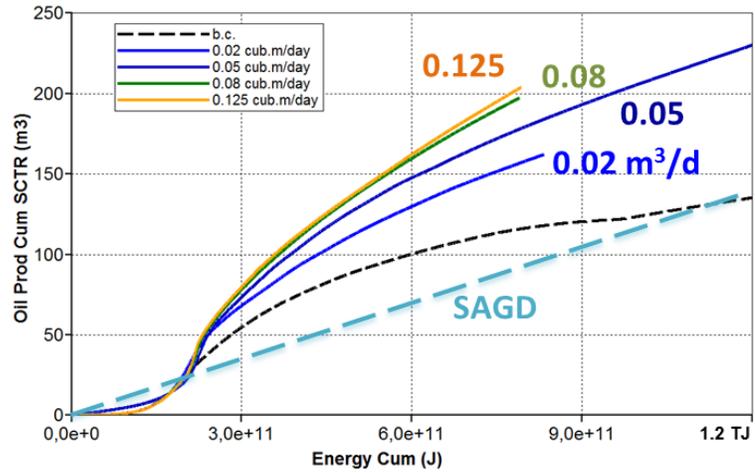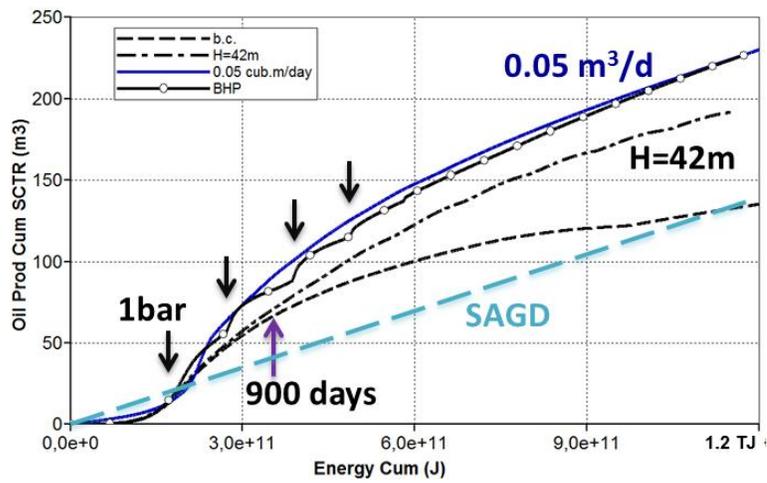
(a)
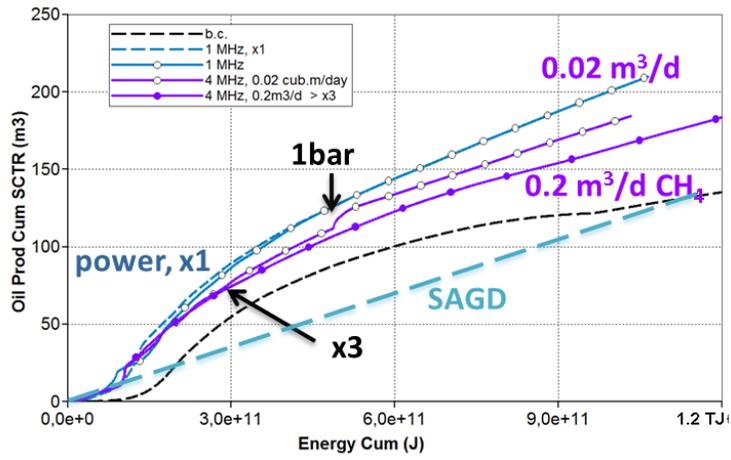
(b)

(c)

Figure 6. Frequency (a) and total power influence on production thermal efficiency at high (b) and low (c) initial water conductivity.

(a)

(b)

Figure 7. Impact on production efficiency of water co-injection at different rate (a) and production pressure variations (b); high water conductivity case.