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Numerical Simulation of Electromagnetic Driven Heavy Oil Recovery

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Abstract

This work presents a feasibility study of a heavy oil recovery process driven by electromagnetic heating (EMH). Previously EMH has been subject of many research works on heavy oil recovery, including laboratory, theoretical and numerical simulation studies. These works have demonstrated that EMH constitutes a promising recovery process; however the simulations of this challenging coupled multi-physics phenomenon were not straightforward and required special efforts in model development.

The major part of previous theoretical and numerical models has been based on simplifications of the Maxwell equations for the EMH source description. The 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 EMH source, i.e. the so-called Beer-Lambert-Bouguer law which, strictly speaking, can be applied to a limited number of practically valuable cases. Other models are required, for instance, to estimate the influence of water evaporation and resulting multiphase flow on EMH driven oil recovery.

Taking advantage of a coupled numerical simulation tool recently developed in our group, a few instructive EMH application cases capturing the effects of EM wave propagation in a non-homogeneous medium, on one side, and thermal multiphase flow in a heavy oil reservoir, on the other, are presented and analyzed in this paper.

Major attention is paid to the production efficiency. Conventional criteria adopted for such an IOR method may not be always applicable, so a comparison to known methods like SAGD or recovery by conductive heating is provided for analysis purposes. Although a number of process scenarios and options are possible, in our current study we chose for the base case a horizontal SAGD-like well pair, the upper well being equipped with an EM wave emitting facility (the EM well). Different process stages (preheating, steam chamber offset and development, and production) are considered in detail and the critical analysis of heating zone and oil flow configurations is done to find out conditions of improved recovery. In particular, the results indicate that while the preheating period can be successfully modeled using the BLB law, starting from the steam chamber offset a more realistic electromagnetic model is to be applied to adequately describe EMH heating source and production dynamics.

The EMH assisted recovery process is a promising IOR method especially for unconventional oil reservoirs. The results obtained in this work via coupled EMH/reservoir flow simulations provide an improved understanding on this challenging multi-physics problem.

Introduction

The world-wide need in new energy sources may be to a large extend covered by heavy and extra-heavy oil-fields in Canada, Venezuella 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.

The thermal methods are well-known for the oil recovery enhancement which is due to substantial decrease of the reservoir oil viscosity at elevating temperature. Being one of the most popular among thermal methods the steam injection is not always successfully applicable, however, in real reservoir conditions. Among the most common reasons for that are the prohibitive heat losses from injection wells and reservoirs, low reservoir injectivity, especially, for bitumen deposits, steam leakage, GHG emission and other environmental problems. Nevertheless, 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 electromagnetic heating (EMH).

Recently, the EMH has been studied as a recovery technique to be applied to hydrocarbon reservoirs, such as heavy oil, bitumen, tar sands, or oil shale (McGee and Vermeulen 2007, Koolman et al. 2008, Carrizales et al. 2010, Davletbaev et al. 2011). Before these although related to experimental results but mainly numerical studies, the EMH has been experimentally and field tested during three decenies.

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. (1985) 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. (1985) tested the IITRI process in application to bitumen reservoirs with initial bitumen viscosity about 10^6 cp which then reduced to 10^2 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 while the recovery factor was between 30 and 70 %.

Sresty et al. (1986) 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 m^3 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 indicated a rapid recovery rate when core samples were heated more than 100°C. The autogeneous drive experiment demonstrated 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 depassing the evaporation temperature.

Among other teams investigated the EMH the Canadian group from Alberta can be mentioned. Chute and Vermeulen (1982) 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 sample. More uniform heating of the payzone has been observed during inductive heating.

McPherson et al. (1985) described the concept of the Electromagnetic-Flood process. The authors proposed to use the horizontal wells as wave guides to facilitate the energy injection.They assumed that the evaporation of the connate water will produce a vapor chamber that progressively will be extended as the heating progresses in time. To accelerate the oil production, they suggested additional displacement factor such as 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. (1994) presented proof-of-concept results for single well EMH, 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. (2008) and later Wacker et al. (2011) have described the technical principles of the EM-SAGD process (SAGD 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 of the EMH, the mathematical description of the process up to now has been reduced to simplified and cumbersome in use (except for analytical models) the so-called Beer-Lamber-Bouguer (BLB) law (Bouguer, 1729; see also Abernethy, 1976, Fanchi, 1993). 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 (Carrizales et al. 2010, Soliman 1997). The connate water evaporation and steam circulation chamber development inside the payzone puts definitely limit to the 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 steam chamber (with zero liquid water content) and the water distribution just outside it are crucially important in simulations. 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. 2010). It launches CMG STARS simulator together with COMSOL electromagnetic (RF) module, 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 whicn are independently adapted each to their specific solutions. The coupling idea realized in EMIR makes possible to directly model the dynamics of EMH coupled with fluid distributions (mainly, water) and based on instantaneous and precise electromagnetic computations. The well configuration similar to those used for SAGD and recently proposed by Kasevich (2008) for the EMH was considered.

Making use of EMIR the 2D bitumen recovery under EMH conditions has been modeled. 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.

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

Physical background and principal mechanisms of oil production

Multicomponent multiphase heat and mass transfer strongly coupled with the electric medium properties and EM field distribution sets a general physical framework of the recovery method. Consider now more in details the physical phenomena taking place inside reservoir during EMH. First of all, remind that in the variety of electromagnetic heating methods (EMH) having the same source of energy (the EM waves) not each method is based on the same mechanism of the energy convertion to heat. Such a mechanism exists at practically all field frequencies but the conversion is not always efficient, for example, because of medium properties variation with frequency. 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.

EMH power field

The field frequency defines the typical size of the heating zone (i.e. the energy absorption length, equation A-5) and gives the heating mechanism. The latter depends also on medium properties, however, conventionally only few of the related phenomena are mentioned in literature. For instance, in case of the low-frequency heating (LFH) it is the Joule effect (for some details of the LFH see Harvey et al. 1979, Hiebert et al. 1986); the high-frequency or microwave heating (HFH, see *e.g.* Sresty et al. 1986) 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 $1\text{-}10^3$ MHz. Finally, the so-called inductive heating (IH, cf. Koolman, 2008) is a direct consequence of sporadic Foucault (eddy) electric current and once again, the Joule effect, and is frequency-dependent in this case. The IH takes place at frequencies $10^{-3}\text{-}1$ MHz and is considered by some authors as a composite effect, since it may take advantage of the Joule effect (till the water remains in liquid state), and of dielectric heating after water evaporation (cf. McPherson et al. 1985). The principle reason, however, why this method is distinguished from other EM methods is not the heating mechanism but the special technique (like for instance, the Litz cable) which minimizes the transmission lines losses.

Mathematically speaking, the system of Maxwell equations (cf. *e.g.* Fanchi, 1993) is known to offer the generalized description of EM phenomena including that part of the field power which is based on effective electric conductivity of a medium (see equation A-2 and discussion below) whatever be the applied EM field frequency and underlying physical mechanisms. 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. Note in this connection that the LFH differs from the other two methods in a sense that its use is limited directly by the existence of an effective electrical circuit or, in other words, a continuous conductive path for electric current between electrodes. So in case of the LFH the reservoir water has to be always in liquid state around electrodes; if the electrical circuit is disconnected, there is no heat release in it with the electrodes becoming burned finally. For high frequencies this is not the case because the EM-waves propagate (without absorption) through a dry porous medium. Obviously, like in case of LFH there is no heat release in a dry medium.

The resulting expression for effective electrical conductivity comprises two terms which take into account mentioned heating mechanisms (cf. equation A-2): the conductivity of moving free electrical charges under the action of electrical field (electrical conductivity, S/m) and the term representing the molecular rotational movement and proportional to medium electric permittivity, C/V/m. At some typical frequency the latter becomes more important; from the physical viewpoint this frequency may logically (and conveniently) separates the inductive and dielectric heating. 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 (Bogdanov et al. 2011a). During the high frequency process the similar conditions of "remote" heating occur naturally after evaporation of a part of connate water as there is almost no heating inside the steam circulation chamber (see Figure 3, left column).

Heat and mass transfer in reservoir

Conductive and convective heat transfer coupled with phase transfer, volumetric heat source and point-wise production heat sink are the main elements of temperature field dynamics. Among other mechanisms the conductive heat transfer is far from being negligible in any EMH based process. This mechanism diminishes the temperature difference inside the reservoir and may even underlie a thermal recovery process where energy injection is done without heating fluid. This may create a strong short-time power density of heating. Bogdanov et al. (2011a) showed that it might be more efficient that EMH for preheating.

However the advantages of the HFH methods, including the IH, include the aforementioned “remote” heating outside a water-free hot reservoir region (a steam chamber) around an EM field applicator. The reservoir water evaporation changes drastically the production mechanism in favour of the gravity drainage, accelerates the energy exchange between heated and cold parts of reservoir and increases, at least locally, the pressure and temperature in reservoir. In-situ steam generation via HFH relates directly the EM methods to SAGD and demonstrates that these methods can be potentially efficient, powerfull and applicable for a wide range of reservoir conditions.

One of promising cases of such application is considered in this paper. Unlike SAGD the HFH driven bitumen production is done mainly via the connate water evaporation and circulation in 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 $SOR=S_{wi}\,(\eta S_{oi})^{-1}$ [m3/m3] (the nomencature is given at the end of paper). Note that SOR is inversely proportional to η and in particular, SOR=1 m^3/m^3 if the recovery factor is S_{wi}/S_{oi}, i.e. approximately 0.25 (cf. Table 1).

However, it may not guarantee that in practice the use of the HFH is not expensive and, as usual, a separate case study is required in advance (Vermeulen and McGee, 2000). Perhaps a major weakness of the method stems from its advantage: without injection the pressure inside steam chamber is restricted by the initial reservoir pressure which obviously limits the temperature there.

Usually, two periods can be distinguished for each EM-driven bitumen recovery, namely, preheating and production (Sresty et al. 1986, McGee 2008). Physically speaking, the principal target of preheating is to deliver a necessary amount of energy to a reservoir before the production of a first (bitumen) barrel happens. At least, the connectivity between wells should be provided at this stage as a result of the reservoir 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 (*e.g.* McGee and Vermeulen, 2007) is possible if additional heat transfer mechanisms are used to avoid the “hot spots” effect. One example of the LFH driven production of such a type has been presented recently (Bogdanov et al. 2011a).

Typical problem scales

In descending order the typical space scales of the 2DC EMH problem are as follows. The spacing between well paires, *L*, indicates the largest problem size which is followed by the reservoir thickness, *H*, the distance between wells in paire, *h*, which concerns mainly the preheating period and, finally, the energy absorption length, *l*. Assume that the EMH takes place at constant total generated power; assume also that $L>>H$ and the well-pair spacing can be defined rather from total production time consideration than from physical mechanisms comparison. Then it is the dimensionless reservoir thickness $\vartheta=H/l$ that characterizes the heating “regime” varying from nearly homogeneous ($\vartheta<1$) to “shallow” heating ($\vartheta>>1$, can be true, for instance, at $h/l>1$). It seems instructive to estimate the characteristic time of preheating t_C (at constant total heat release) which may be defined as time when the temperature at the production well reaches certain value. It can be shown that for both ultimate regimes this characteristic time scales like $t_C \propto l^2$ (and so does the time of evaporation offset near EM applicator, t_B). This can be directly used in the field frequency choice in preheating design considerations.

Simulators coupling framework

Using the BLB law and a simplified problem formulation it is possible to develop useful analytical solutions providing feasible estimates and predictions (cf. Carrizales et al. 2010). Unfortunately, to our knowledge no one standart reservoir simulator conventionally incorporates the description of such method like the EMH (one exception is the electrical heating option in CMG STARS, 2010). So to work with such a model one has either to develop a new simulator or to couple an existing code to another phenomenon-specific code. We have chosen the latter way and worked out a project of code capable to launche and control the data exchange between the reservoir simulator and COMSOL Multiphysics (2008). A 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. This recently developed and tested in-house code did carry out coupled simulation of the EMH applications for bitumen reservoir.

The 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 (Torres et al. 2010). A finite-volume reservoir simulator solves its usual energy and component 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 compositon- and temperature-dependent reservoir properties is done using coupling code utilities and the results are stored on the finite element grid. Furthemore, 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 special mapping are specified for the common subdomain. 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 (*e.g.* Torres et al. 2010).

Problem formulations and parameters

The EMH driven bitumen production can be done via field applicator (electrode, cable, antenna etc.) installed directly in a special (EM) 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 reffered to as 2DC. The chosen well pattern is similar to well-known SAGD pair of horizontal wells, the production being done via those in bottom of reservoir (cf. Kasevich, 2008). 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 grainage 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 burden layers (to top and bottom of the reservoir) were added to compute more precisely the EM field and power distribution, and also the heat losses from reservoir. Though different options are available to model the EM field propagation in COMSOL, the harmonic field equations (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 applicator to reservoir interaction and the transmission lines parameters. Some details of such a modeling can be found elsewhere (Godard and Rey-Bedbeder, 2011). It follows that by the total energy in our results we mean the total cumulative heating energy, i.e. the part of the EM power converted to heat in the reservoir. Transmission line losses and 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 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 law flowrate. The study cases included the EMH 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 (Bogdanov et al. 2011b). To set a physically feasibile reference to the EMH cases under consideration, the recently published modeling results on the LFH (McGee and Vermuelen 2007; Bogdanov et al. 2011a) and the bitumen recovery with pure conductive reservoir heating are used below. The total list of runs done and considered in our current work can be found in Table 3.

Simulation results and discussion

Both the preheating providing favorable conditions to start and the production itself, are important events for our modeling and discussed below. Each of these stages is capable to contribute much into final result and we'll try to clarify how it was to understand better how it can be.

Preheating

Although the preheating is technically more involved in practice than it was in simulations, the detailed study of preheating is still to be done. The preheating regime may be defined by two characteristic times: first one, t_C, necessary to increase the temperature at the production well to a target value and thus, to provide the well connectivity, and second one, t_B, which corresponds to a water evaporation event at the EM well. Then two different regimes can be recognized:

(1) in case if $t_B<t_C$, a strong local heating is accompanied by fast evaporation of connate water in a relatively small volume with further expansion of the steam chamber driven by "shallow" EMH (in a sense that the heating is localized very close to the steam chamber surface); as a result the principal mechanism of oil recovery is evidently the gravity drainage. The pressure increases sharply at the EM well if the steam generated here is not withdrawn. This regime may be envisaged at relatively small initial water saturation and is physically close to drying in high-frequency EM field;

(2) in the opposite case, $t_B > t_C$ (i.e. preheating "without" evaporation), the relatively slow volumetric heating of wide enough reservoir region which make even possible, probably, the oil production by a known secondary or tertiary method (or their combination). Either lower frequency or pure conductive heating (which may also be "resistive" if it uses electrically heated load inside the well) should be applied with effective temperature control imposed at the heating end.

In our case, at frequencies 1MHz and higher, the short-time heating without special temperature control tends to follow the scenario (1) and then gradually may turn partially or totally to (2). The reason was quite natural, namely, the initially nearly singular power field around the applicator and, at late time, the power decay with distance and the conductive heat transfer providing more important volumetric heating effect. In our study we used the pure conductive preheating for high-frequency field cases which are referred in right column of Table 3 to as “preheating” runs. The conductive preheating improved early production (cf. *e.g.* the curves at different frequencies in Figure 7c) but didn’t influence, probably, the long-time production efficiency.

One of the advantages of EMH methods consists in the ability to adapt the heating to different conditions of real deposit (*e.g.* Carrizales et al. 2010) and due to this, in possible efficient control of process. Theoretically, the more homogeneous is the temperature rise in reservoir, the better. This idea has been developed and tested, for instance, by IITRI (Sresty et al. 1986). However, in practice it seems to be less definite. Unlike the LFH where the water evaporation has to be avoided, it may be acceptable and desirable for the heating at higher frequencies. The fast local evaporation of a certain fraction of connate water may lead to acceleration in oil heating by the steam convection and to production enhaced by gravity drainage. The variations of wave frequency and total EM power offer the process-control means which may be more efficient in combination with the monitoring of the reservoir. Remind that the evaporation (at IH or HFH) leads to “remote” heating beyond the steam chamber (cf. Figure 3a-c) which is much in common with the circulation chamber at LFH and may be used to control the heating field configuration.

Production efficiency factors

As already metioned the production results directly depend on how efficiently the thermal energy is used in reservoir. The typical power and temperature fields for different cases are shown in Figures 3,4. Figure 4 presents the instantaneous electric field computed and visualized with the multiphysics simulator (a), the water saturation field that reflects the reservoir electric properties variation and for this reason shown in inverse color (b) and their resulting combination (product) i.e. the heating power (c). At this frequency the electric field doesn’t penetrate deep into the region with liquid water (outside the blue color in Figure 4b) and the heating field remains “shallow” i.e. follow the surface of steam chamber and variations of water saturation along it.

The power field in Figure 4c is qualitatively similar to that in Figure 3c. The latter corresponds to shorter process with higher input power of the same frequency (see Table 3). The fields in Figure 3 corresponds to the same amount of cumulative heating energy generated in reservoir and the same interwell distance h=10m. Lower frequency field (Figure 3b,e) makes the power field less compact and changes narrow enough oil flow configuration looking much in common to typical SAGD flow configuration (Figure 3c) to wider flow bands. Note the curious S-shaped flow-lines in both cases.

At greater thickness more isotropic temperature field and even less restricted oil flow configuration can be seen (Figure 3a,d). During long time the heat exchange with burdens are small in this case and the production efficiency is better. In particular it follows that the heat distribution parameters like $\vartheta=H/l$ define above, are important in definition of the production optimal conditions.

Fluid flow pattern

Fluids thermal expansion and water evaporation create favorable pressure difference for hot oil production. The usual fluid flow-line distributions during production period are shown, for instance, in Figure 3. At late stage, however, the increasing heat loss and continuing hot production diminish the energy accumulation rate in reservoir. This may result in unfavorable phenomena affecting the fluid velocities and the production rate. The general flow pattern at production stage is similar to typical flow distribution for SAGD and can be characterized as ascending steam (or gas) flow and descending liquid flows. This remains valid until the energy input is sufficient to maintain the pressure in the steam chamber.

In the opposite case the deacreasing pressure may perturb the flow pattern driven by gravity dranaige and prevent a significant volume of hot oil to reach the producer, as it is shown in Figure CON. As normal at gravity drainage, the pressure variation should not be high to turn up the local oil velocity and thus to drop the production rate. Below is explained how the production reacts when energy input becomes insufficient (cf. Figure 5). To avoid such a consequence and to maintain a pressure in the steam chamber a small amount of steam (<1/20 m^3/day sc) has been injected in some cases (cf. Table 3). This can be considered in the similar framework of the temperature control like water injection during electric heating described *e.g.* in McGee and Vermeulen (2007), Bogdanov et al. (2011a).

Production efficiency

At equivalent cumulative energy generated in reservoir the gravity drainage provides faster production in case with smaller heat loss and more uniform temperature field in reservoir. Ideally the latter means that the temperature field should not be isotropic but follow the reservoir geometry. It is particularly important to keep the temperature at producer as close as possible to the steam chamber one. Because of the well position this contradicts the need to minimize heat loss and makes a problem less evident.

Power and frequency variations

These two parameters of the EMH driven recovery can be a powerful mean to control the process from the surface. Along with this the problem to find out the optimal production conditions in terms of power and field frequency is not straightforward. For example, the direct comparison of results for two different field frequencies at equivalent cumulative heating energy is done in Figure 6. It can be seen that the steam chamber and temeperature field is somewhat wider and penetrated deeper in the reservoir (cf. blue and red zones, respectively, in Figure 6a,d and 6c,f) for higher frequency; moreover, the oil flow band is definitely wider in this case like indicate the arrows of the fluid velocity. Despite this the production summary analysis shows more efficient production in the lower frequency case, cf. Figure 7a. The temperature field comparison indicates the greater heat loss to cap rock and lower temperature at reservoir bottom in general and at production well in particular, in the first case. This explains the difference in production efficiency which remains small, however.

It can be shown that both power and frequency reduce the typical time of temperature rise and the subsequent expansion of the heated oil volume. The production results for approximately double power shown in Figure 7c demonstrate similar process efficiency dynamics and therefore the potential for futher reduction of the process time.

Pressure variations and maintenance

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

It has been demonstrated recently that the recovery mechanism can be enhanced by stable gravity-assited displacement provided for instance by a gas injection from the upper section of the well (Wacker et al. 2011). Taking advantage of idea described by McGee and Vermeulen (2007) 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 flow-rate of about 0.05 m^3/day (in liquid water equivalent) improved considerably the production whatever be the EM field frequency and power (Figure EFFb,c). 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. 2011b). The BHP pressure has being deacreasing (at rate about 1.2bar/year) once per year during 5 years. This has led, first, to recovery enhancement (see black line in Figure 7b and grey line in Figure 7c at 500 GJ generated) and confirmed, second, that combination of the EMH with pressure operations can improve the production rate, the oil recovery factor and hence the global efficiency of the process (Figure 7). The best EOR (ratio of energy consumed to oil produced) reached in our study varies within 4 and 5.5 GJ/m^3, the latter being the reference even for long-time production.

Conclusions

Taking the main process parameters considered here, namely, the production rate and the thermal efficiency of recovery process one may state that:

- the EM heating power field and its evolution during oil production period may be computed more precisely and efficiently making use of dedicated simulators and coupling code developed recently.
- our numerical analysis shows that the EMH assisted bitumen recovery is a promising method with thermal efficiency comparable to and potentially better than that of SAGD even if the supplementary EM energy loss in transmission lines is considered.
- for the EMH application via couple of horizontal wells (SAGD-like well pair), the more homogeneous heating is advantageous for bitumen recovery. The adequate choice of the EM field power and frequency may improve the process efficiency.
- the EMH assisted bitumen production stimulation can be done by law rate steam co-injection or production pressure variation.

Nomenclature

Roman letters

c = 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_e = wave number (reservoir), 1/L, 1/m
l = energy absorption length, L, m
m = power in Archie's law for electric conductivity, n
t = time, t, s
t_C = characteristic (control) time of preheating, t, s
H = reservoir thickness, L, m
J = heating power source term, m/L^2t, W/m^3
L = 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 = horizontal space variable, L, m
Z = vertical space variable (depth equivalent), L, m

Greek letters

β = lithology parameter in Archie's law, n
ε_0 = electric constant (void space electrical permittivity), q^2t/L^3m, 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
σ = effective bulk reservoir conductivity, q^2t/L^3m, S/m
σ_B = bulk electric conductivity of reservoir, q^2t/L^3m, S/m
σ_w = water phase electric conductivity, q^2t/L^3m, S/m
ϕ = porosity, n
ω = angular EM wave frequency, 1/rad
K = bulk reservoir heat conduction coefficient, mL^2/t^3LT, W/(m K)

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Appendix A.

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 permttivity for which linear mixing law has been chosen. The latter 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, $i=(-1)^{1/2}$. The standard formulation of Archie's law (without temperature dependency factor) is used in current work which reads as

$$\sigma_B = \beta\sigma_w\phi^m S_w^n . \tag{A-4}$$

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 is important enough to be specified here. It is so-called energy absorption length which characterizes the heating power attenuation (cf. Fanchi, 1993) and may be written as

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

which gives for non-conducting medium at $|\varepsilon_r|>>1$,

$$l \approx \left(\sqrt{2}k_e \right)^{-1} . \tag{A-5b}$$

Here $k_e=k_0\varepsilon_r^{1/2}$, $k_0=\omega/c$ is the EM wave number and c speed of light, both taken in empty space.

EM field model

Harmonic EM field formulation has been used for computation of power density term given by (A1). The electric field was determined either from resulting equation for the harmonic field that may be written as

$$\nabla\times\nabla\times\mathbf{E} + k^2\mathbf{E} = 0 , \tag{A-6}$$

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

$$\nabla\times\mathbf{E} = i\omega\,\mathbf{B} . \tag{A-7}$$

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.

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/m^3/°C
Burdens volumetric heat capacity	$2.01 \cdot 10^6$	J/m^3/°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	0.0087	S/m

TABLE 2. ROCK AND FLUID PROPERTIES USED BY NUMERICAL MODELS

Component	Phase	Density, mol/m^3	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	$8.00 \cdot 10^{-4}$	$5.5 \cdot 10^{-7}$	$4.00 \cdot 10^3$

TABLE 3. LIST OF EMH CASES PRESENTED

Thickness	Water Injection	Production well BHP	Operational Conditions
H=22m	No	No	100 kHz
H=42m	No	No	100 kHz
H=22m	0.02 m^3/day, from 450 days 0.05 m^3/day, idem 0.125 m^3/day, idem	No No No	100 kHz
H=22m	No	1.2 bar/year	100 kHz
H=22m	0.05 m^3/day idem	No No	1 MHz, preheating 1 MHz, preheating, double EM power
H=22m	No	No	4 MHz, preheating
H=22m	0.02 m^3/day, from 360 days	1 bar at 1200 days	4 MHz, preheating
H=22m	0.05 m^3/day, from 360 days	No	4 MHz, preheating

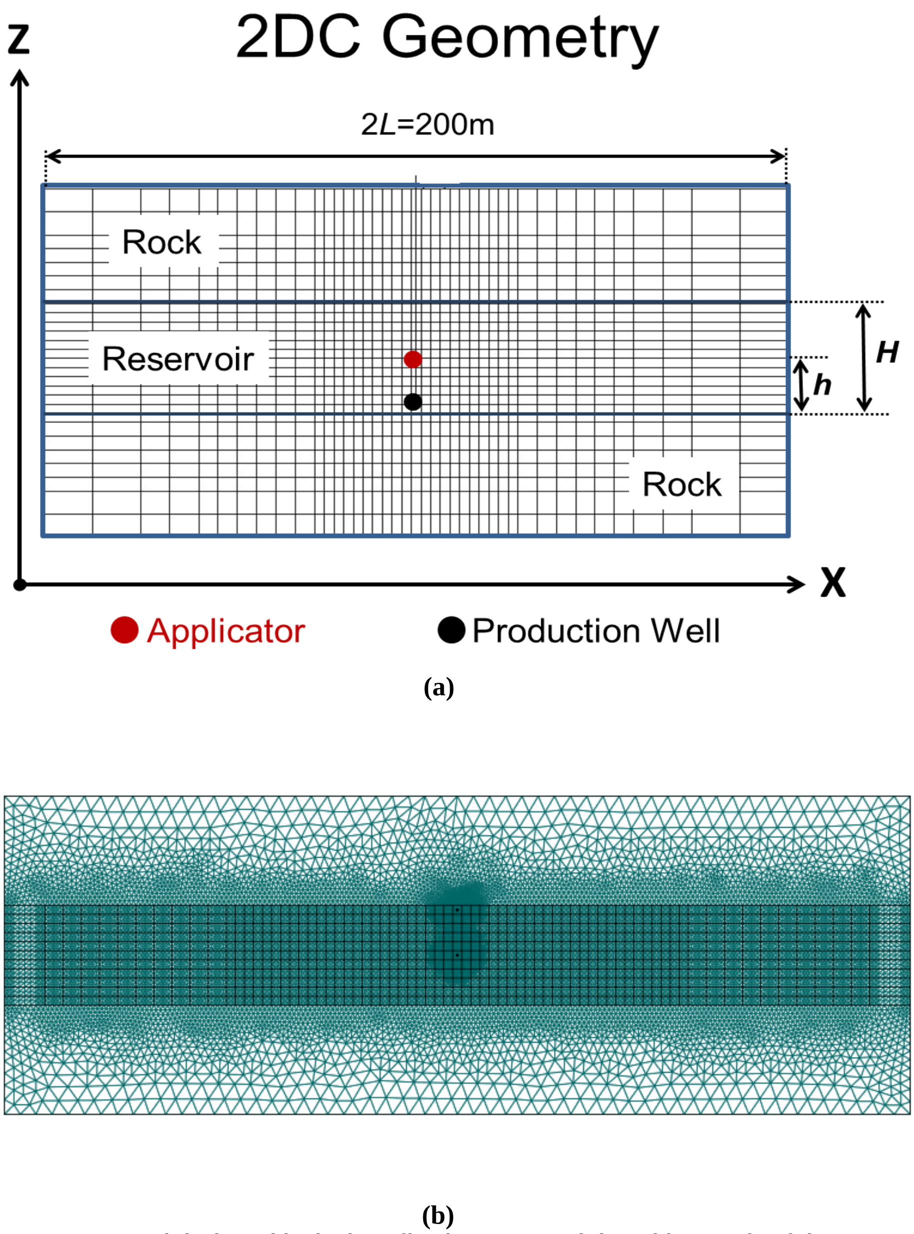


Figure 1. Problem geometry and design with single well pair pattern and the grid example of the reservoir simulator (a); example of finite elemnet grid for our 2DC problem (b).

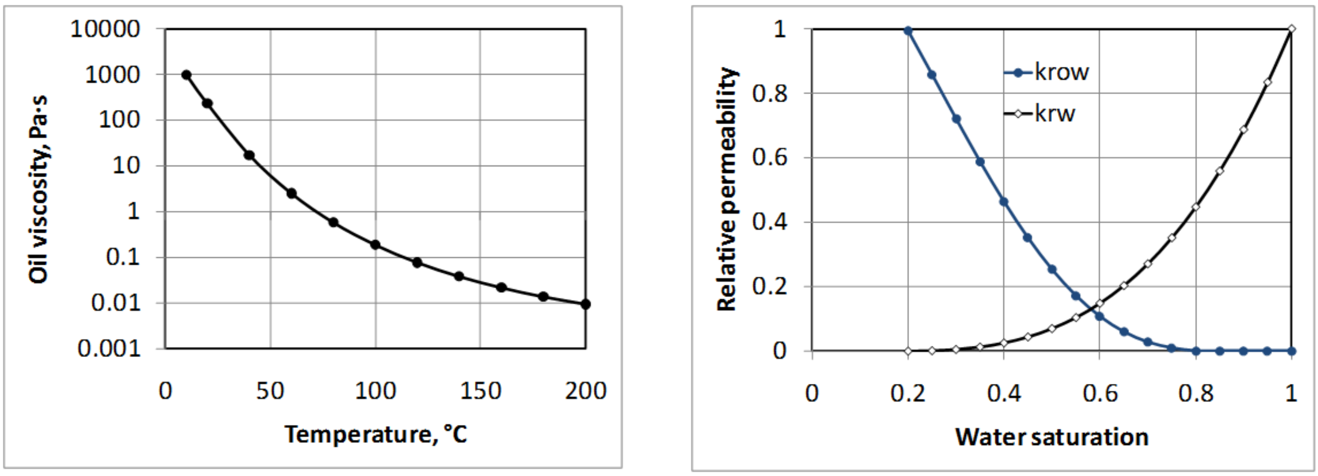


Figure 2. Common for all runs input data for the oil and water transport properties.

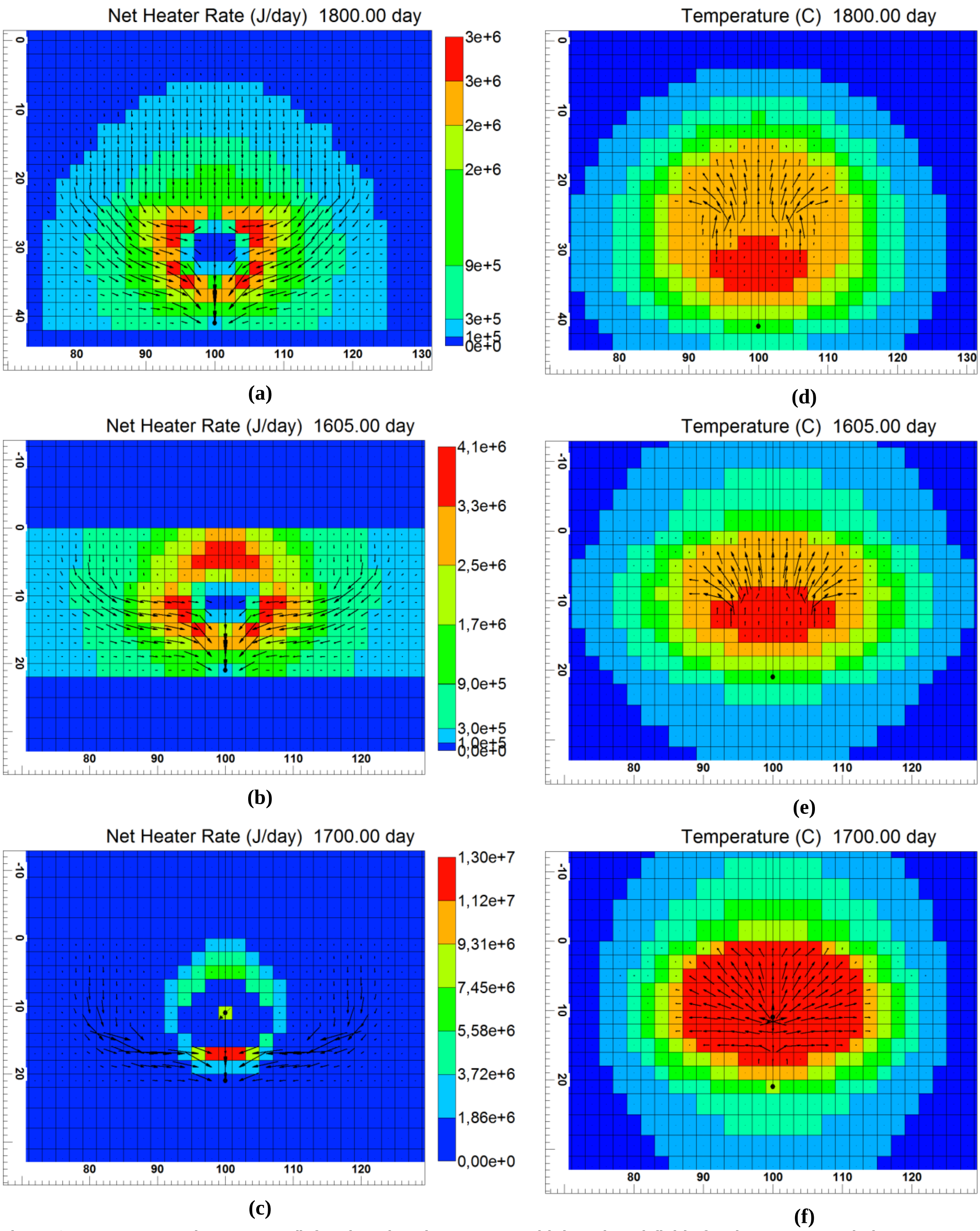
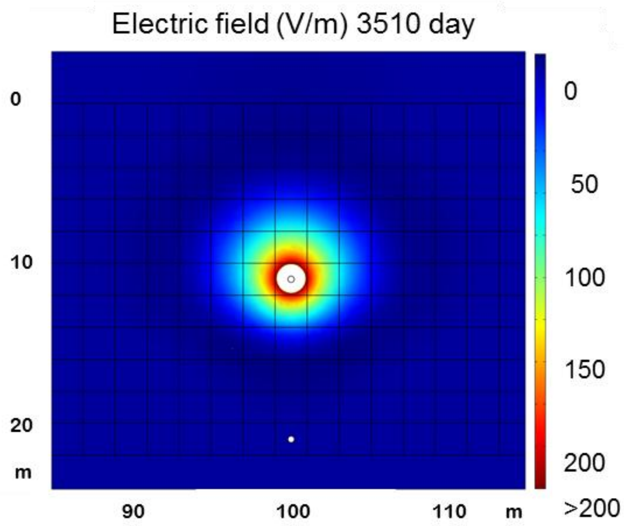
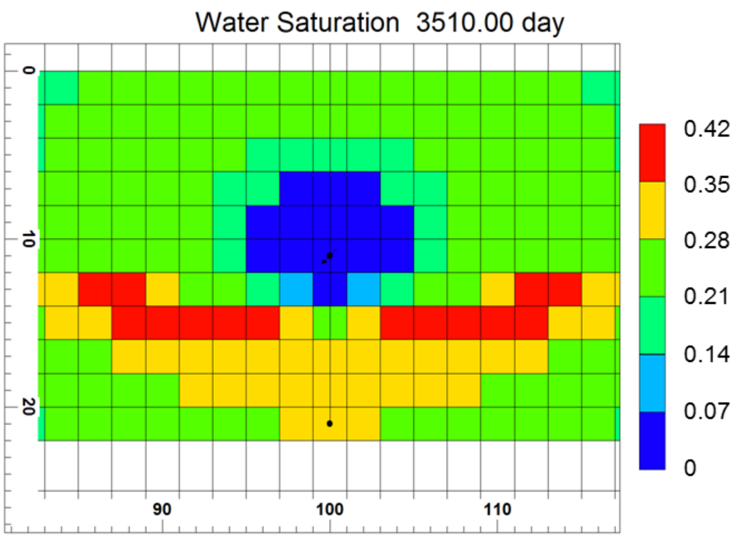


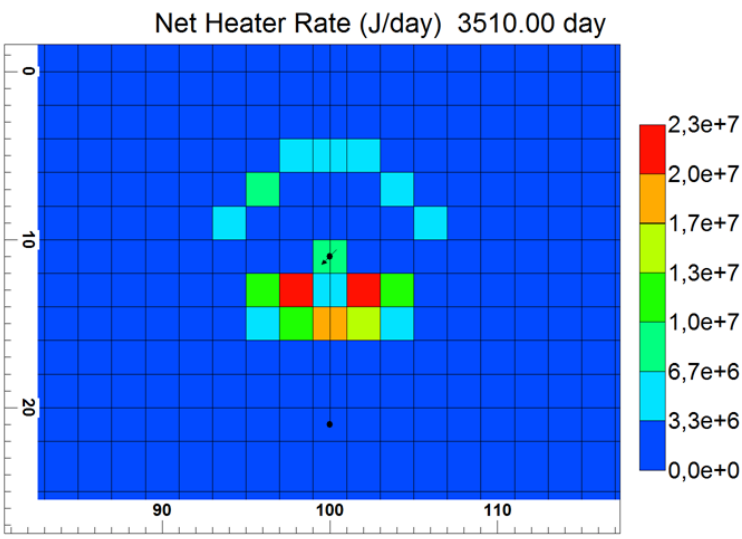
Figure 3. Instantaneous heat source (left column) and temperature (right column) fields for the same cumulative energy generated at *H*=42m, *v*=100kHz (a,d); *H* =22m, *v*=100kHz (b,e); *H* =22m, *v*=1MHz (c,f). Arrows indicates oil (left column) and gas (right column) local velocity direction and magnitude. At *H*=42m the reservoir top and bottom are at z=0, 42 and at *H*=22m, z=0, 22m, respectively.



(a)



(b)



(c)

Figure 4. The electric field around applicator (a), water saturation (b) and power field (c) at *H*=22 m, *v*=4MHz.

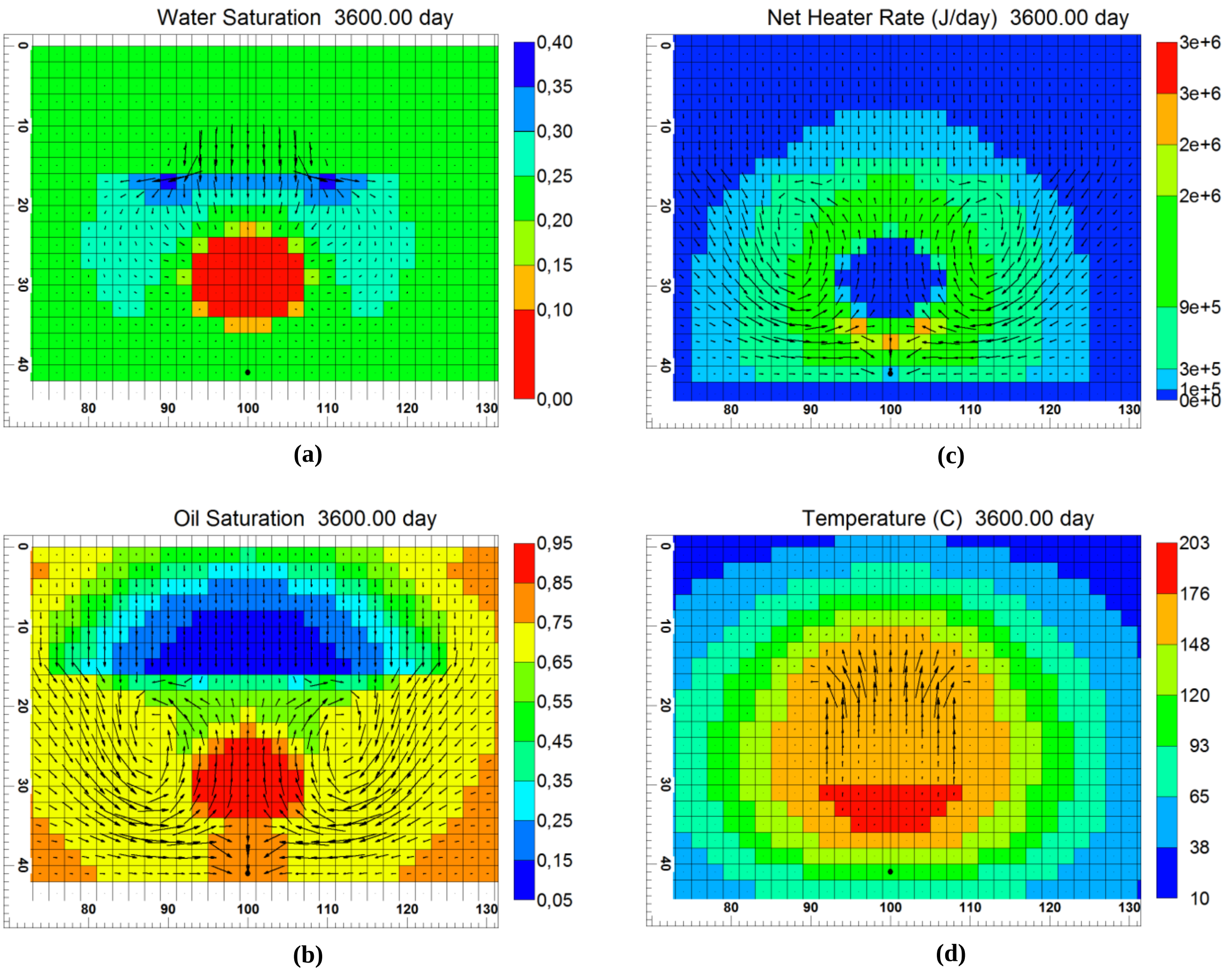


Figure 5. The hot oil circulation in heated zone at late EMH stage, *v*=100kHz, *H*=42 m.

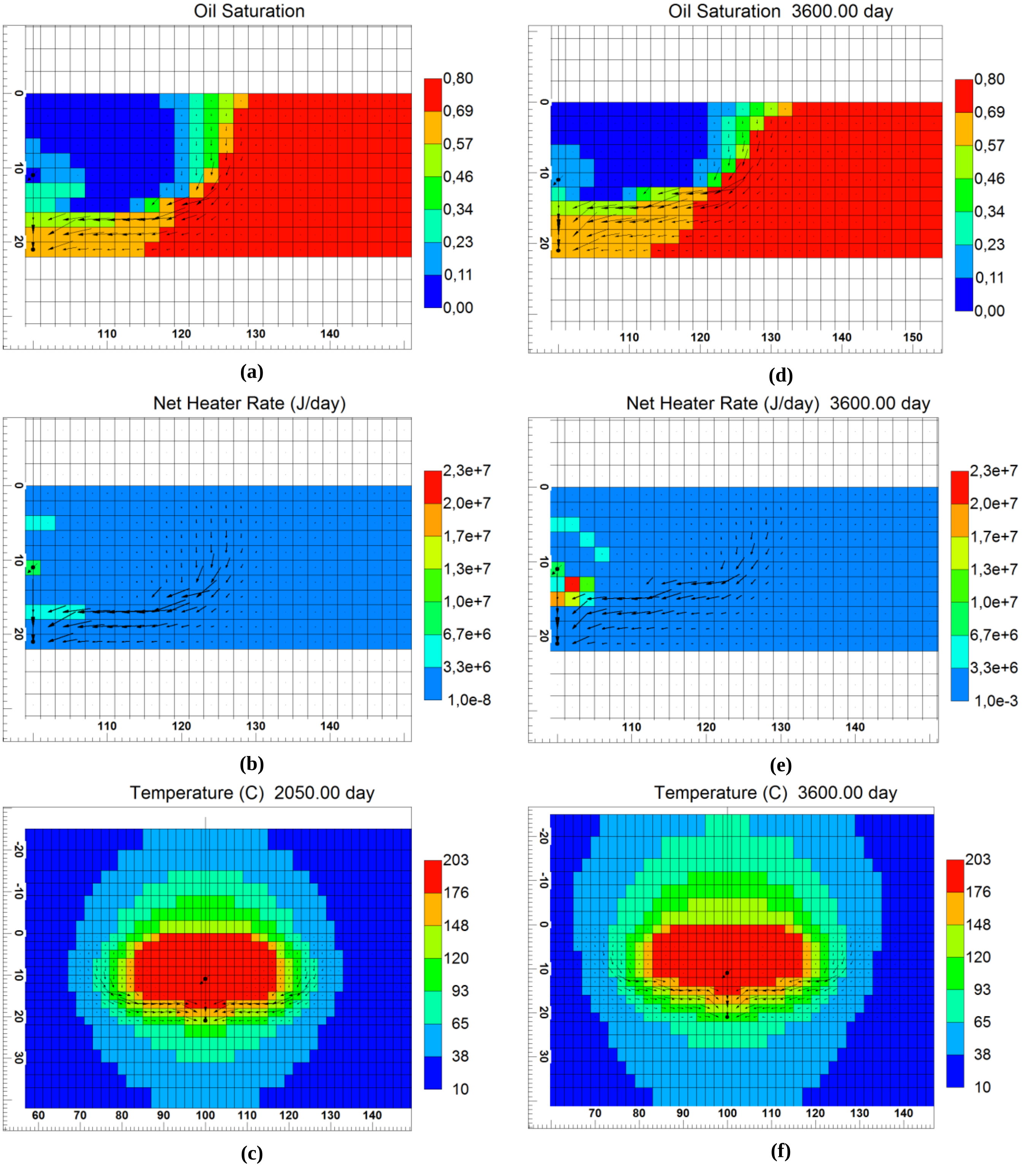
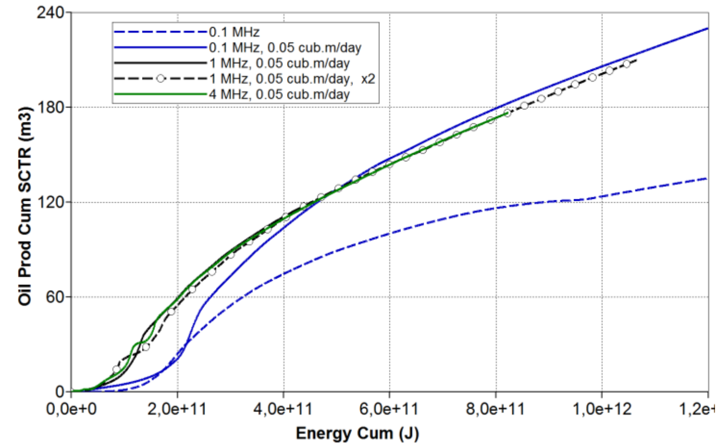
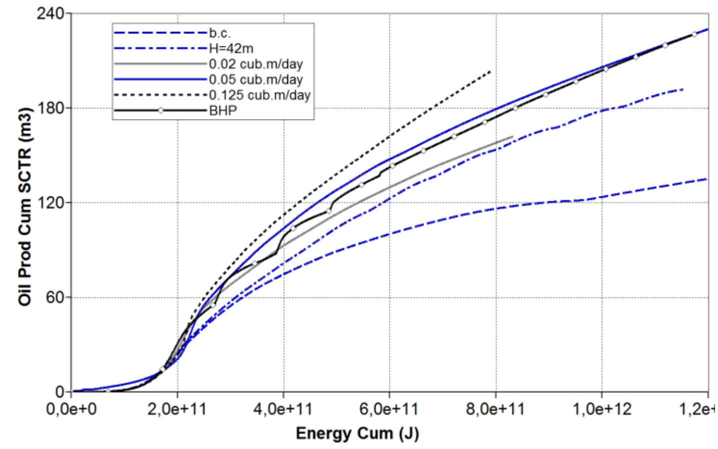


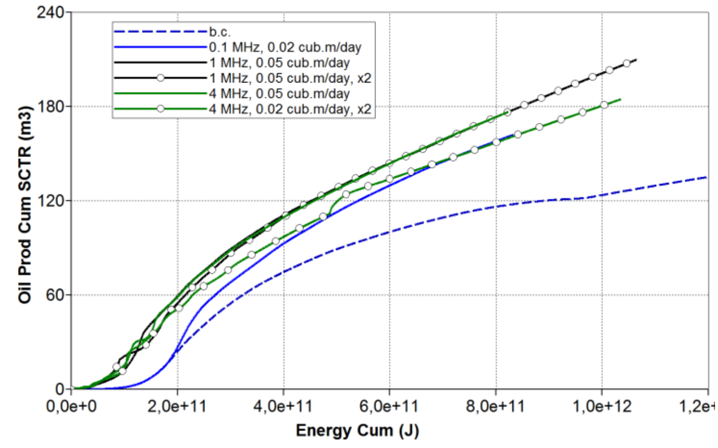
Figure 6. The EMH based recovery at *v*=100kHz (left column) and 4MHz (right column) Oil saturation (a,d), heating power (b,e) and temperature fields at equivalent cumulative energy generated in reservoir. Arrows show the oil local velocity direction and magnitude.



(a)



(b)



(c)

Figure 7. Thermal efficiency of oil production by the EMH: the effect of steam coinjection at different field frequencies and increseang the EM field power (factor 2) – (a); summary of production efficiency results at 100kHz (b); results of the power increase at high frequencies (c); the results at *v*=100kHz have been added for reference.