CHEMICAL ENGINEERING TRANSACTIONS
VOL. 32, 2013
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at: www.aidic.it/cet
Chief Editors: Sauro Pierucci, Jiří J. Klemeš

ISBN 978-88-95608-23-5; **ISSN** 1974-9791
DOI: 10.3303/CET1332210

A New Technique for Heavy Oil Recovery Based on Electromagnetic Heating: System Design and Numerical Modelling

Alessandro Cerutti[a], Mauro Bandinelli[a], Matteo Bientinesi[b*], Luigi Petarca[c], Michela De Simoni[d], Matteo Manotti[d], Giuseppe Maddinelli[d]

[a] IDS Ingegneria dei Sistemi, via Enrica Calabresi 24, Pisa, Italy
[b] Consorzio Polo Tecnologico Magona, via Magona, Cecina (LI), 57023, Italy
[c] Dipartimento di Ingegneria civile e industriale, Università di Pisa, Largo Lucio Lazzarino, Pisa, 56124, Italy
[d] ENI, Exploration and Production Division, via Emilia 1, San Donato Milanese, Italy
* matteo.bientinesi@polomagona.it

The importance of heavy oils as energy resource is continuously increasing, thanks to the development of enhanced oil recovery methods, such as thermal recovery. Radiofrequency reservoir heating through a downhole antenna system can be an effective alternative to steam injection methods, giving advantages such as good energy distribution, greater independence from reservoir properties, equipment compactness, high efficiency and possibility to focus the energy on the oil bed. In this paper we present a numerical study of a new electromagnetic heating method, which combines a radiating antenna with a well-reservoir interface structure, called tight shell. The study was conducted adopting dielectric and physical parameters measured on real oil sand samples and heating requirements relative to an actual oil sand reservoir. The study aims to evaluate the optimal operating irradiation frequency, as well as the effectiveness of the tight shell interface. Results show that, with a proper system design, a considerable volume of reservoir can be uniformly heated by a single downhole antenna. Frequencies in the 10-20 MHz range give the best results, and the use of a tight shell made of a low-loss dielectric material surrounding the irradiating element proves extremely efficient in lowering peak temperatures at the radiating well, preserving well completion and extending the heated volume. The use of a tight shell makes also the method much less sensitive to possible dishomogeneities in the dielectric properties of the reservoir material.

1. Introduction and system design

Radio Frequency (RF) irradiation can be a sound alternative for thermal heavy oil recovery, since it is less affected by formation geology and is capable to distribute heat over a large reservoir volume. Other advantages are equipment compactness, high efficiency and the possibility to focus the energy on oil bearing strata, reducing heat losses through the overburden.

Quite a small amount of modeling and experimental studies have been reported. Sresty et al. (1986) and Kasevich et al. (1994) demonstrated experimentally the feasibility of EM heating of heavy oil, evaluating possible downhole irradiation technologies and process economics, but they did not succeed in measuring temperature profiles either in lab-scale or in field-scale experimentations. Ovalles et al. (2002) and Carrizales et al. (2008), through the use of numerical simulations, compared EM heating assisted heavy oil extraction with cold production and other EOR techniques, evaluating the energy gain and the increase of the productivity index, but they completely neglected the fundamental role of connate water evaporation and they did not investigate the effect of RF operating parameters on the heating process. There is a lack of agreement on what is the best transmission frequency, with proposed frequencies varying from 10 MHz (Kasevich et al., 1994) to several GHz (Sahni et al., 2000).

Please cite this article as: Cerutti A., Bandinelli M., Bientinesi M., Petarca L., De Simoni M., Manotti M., Maddinelli G., 2013, A new technique for heavy oil recovery based on electromagnetic heating: system design and numerical modeling, Chemical Engineering Transactions, 32, 1255-1260 DOI: 10.3303/CET1332210

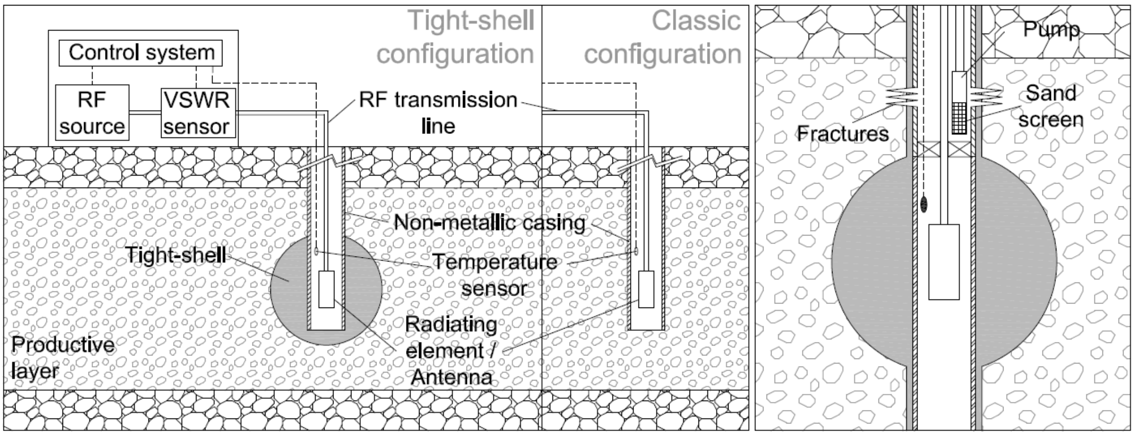

Figure 1: Scheme of the RF radiating well in the tight-shell configuration and in the classic configuration (left) and particular of a possible radiating/producing well completion with tight shell (right).

Moreover, little attention has been paid to the temperature reached near the wellbore during the irradiation process. High reservoir heating rates require a high EM power to be irradiated by the downhole antenna, turning out in extremely high EM fields in the volume surrounding the antenna. Reliable RF heating processes must take into account the EM energy distribution through the reservoir and must be designed to achieve a volume heating as uniform as possible. This is a key factor to prevent the exposure of well completion components to extreme temperatures, while irradiating high EM power rates into the reservoir.

In the present work, a novel RF method which combines a downhole antenna with an interface structure (called tight shell) realized between the radiating well and the reservoir is proposed. The method is schematically depicted in Figure 1 (left), where it is compared with the classic configuration. In one possible embodiment, the system includes:

- an oil producing well (whose completion scheme, depicted in the right side of Figure 1, is specially designed in order to host the RF/MW components and to allow EM irradiation);
- a high power RF/MW energy applicator (composed by a surface unit with a high power RF/MW energy source, a downhole transmission line and a bottom hole antenna);
- a tight shell (a spherical or cylindrical structure interposed between the oil well and the reservoir, realized at the antenna installation depth through drilling and completion operations; the tight shell must be made of a low-loss dielectric material and be impermeable to reservoir fluids).

The same conceptual design can be applied also in configurations where the oil producer well is separated from the radiating well.

In the right side of Figure 1, a particular of a possible completion for a radiating and producing well is depicted. The oil is extracted in a separate section of the well immediately above the section where the radiating element is installed. Fractures in the cement allow the oil to enter the well. The casing must be non-metallic in the radiating section of the well, while in other zones a metallic casing can be used.

In this article the tight shell, for simplicity, was modeled as a spherical element, as depicted in Figure 1. Indeed, a cylindrical tight shell, which has a similar effect on energy distribution and on temperature profiles, would probably be easier to realize.

Based on the new system design, a wide spectrum numerical study of the RF/MW reservoir heating process was conducted. The novel tight-shell RF method was compared to a RF method without such interface. Numerical simulations have studied the optimal operating frequencies to achieve a homogeneous reservoir heating, the effectiveness of the tight shell solution and the impact on the thermal process of key dielectric and thermal properties of reservoir materials.

In a parallel paper (Bientinesi et al., 2013), an experimental test aiming to validate the tight-shell design is described.

2. Model description

2.1 Physical background

The model developed aims to describe the heating of an oil reservoir under RF irradiation through an antenna installed inside a wellbore, at an oil bearing level, at different frequency and power and in static condition. No fluid flow is considered, thus only the absorption of electromagnetic energy by the lossy reservoir material and the heat transport by thermal conduction determines the evolution of the temperature field in the reservoir, according to the thermal energy conservation equation:

$$\rho_{eff} C_{eff} \frac{\partial T}{\partial t} - \nabla \cdot (K_{eff} \nabla T) = q \tag{1}$$

where $\rho_{eff}C_{eff}$ and K_{eff} are the effective heat capacity and the effective thermal conductivity of the reservoir material respectively, and q is the heat source term which accounts for the energy released per unit time and per unit volume by the EM field into the reservoir. The EM problem was included in a simplified form by introducing the equation that describes the main process of energy distribution through the reservoir, driven by the attenuation of the EM spherical wave that propagates through the medium (Von Hippel, 1966), expressed by the following equation:

$$\frac{dP(r)}{dr} = -2\alpha P(r) \tag{2}$$

where P is the EM wave power per unit solid angle irradiated by the antenna, r is the coordinate along the wave propagation direction and α is the EM wave attenuation coefficient. These latter parameter is not actually constant, but varies with time and with the spatial coordinate, since it is a function not only of the frequency but also of the complex dielectric permittivity of the material, which is due to change in terms of composition (solid matrix, oil, connate water) during the irradiation and the consequential heating:

$$\alpha = \alpha(f, \varepsilon^*) = \frac{2\pi f}{c} \sqrt{\frac{\varepsilon'}{2} \left(\sqrt{1 + \left(\frac{\varepsilon''}{\varepsilon'} \right)^2} - 1 \right)} \tag{3}$$

Once provided the solution of the EM power field P(r), the heat source term can be calculated with:

$$q = -\vec{\nabla} \cdot \vec{F} \tag{4}$$

$$F(r) = \frac{P(r)}{r^2} \tag{5}$$

where F(r) is the EM energy flux.

2.2 Water vaporization

During the reservoir heating, the connate water will evaporate and its evaporation will be completed after the temperature exceeds the boiling point (T_{boil}) at the reservoir pressure. Since connate water is the most lossy component in the rock-oil-water mixture, its vaporization is expected to reduce significantly the real and imaginary parts of the reservoir dielectric permittivity. The model was configured to take into account water vaporization, by defining three zones, with different dielectric and thermal properties:

- water saturation zone ($T < T_{boil}$): dielectric and thermal properties of the reservoir are those of the rock-heavy oil-water system;
- boiling layer zone ($T \sim T_{boil}$): transition phase for a little interval around T_{boil}; the reservoir thermal capacity is calculated so as to include the water evaporation latent heat;
- dried zone ($T > T_{boil}$): dielectric and thermal properties of the reservoir are those of the rock-heavy oil system, from which water has been removed.

The extension of the different zones varies with time during the electromagnetic irradiation, in function of the reached temperature.

2.3 Reservoir material properties

The setting of reservoir material parameters in the model is based on dielectric and physical characterization, carried out on oil sands samples. The real and imaginary part of dielectric permittivity (in the 10-2700 MHz frequency range and in the 20-125 °C temperature range), the effective thermal capacity (in the 20-250 °C temperature range) and the effective thermal conductivity (in the 20-150 °C temperature range) were measured (Sarri et al., 2012). For the dielectric permittivity, results show an abrupt change both in the real and in the imaginary part above water vaporization temperature (100 °C at room pressure, see Figure 2). Once all water is vaporized, the dried sand matrix filled only with heavy hydrocarbon is modestly lossy, with a dielectric loss value (ε”) of about 0.01.

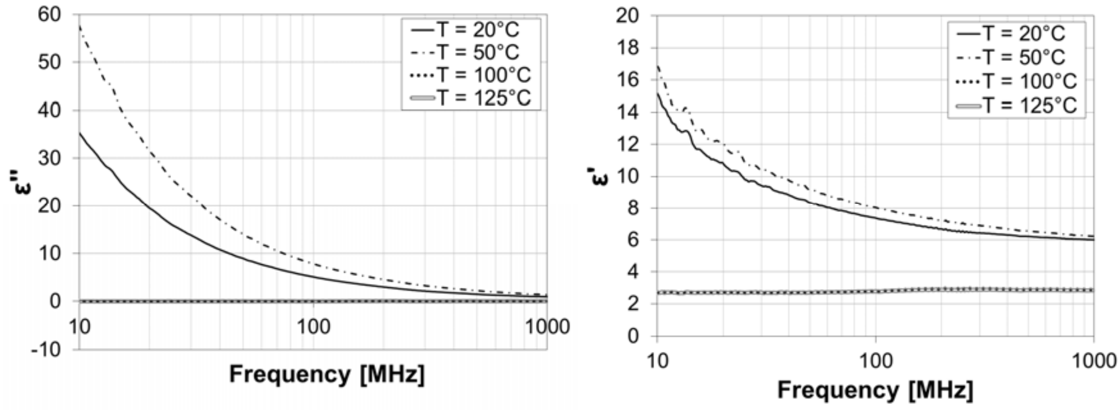

Figure 2: Measured dielectric properties of oil sand samples from room temperature up to above the connate water boiling temperature (Sarri et al., 2012).

However, considering the complex and variable nature of both mineral and hydrocarbon components, a range of values for the dielectric loss of the dried reservoir material was introduced in the model (ε'' = 0.01 - 0.1). In this way, the sensitivity of the RF heating process with respect to this uncertain reservoir property can be analysed.

The experimentally measured values were used to create polynomial expression capable of interpolate the properties of interest (thermal capacity, thermal conductivity, real and imaginary part of the dielectric permittivity) in function of the temperature and of the composition of the reservoir material, in terms of solid, oil and water content. These expression were introduced in the model.

2.4 System parameters

The viscosity of the bitumen (oil fraction) contained in the oil sands samples decreases to 0.1 Pa·s at temperatures higher than 100 °C. Over this temperature, the bitumen can be considered mobile and can thus be produced. Numerical simulations were thus carried out in order to evaluate the feasibility of a uniform heating process, capable of rising reservoir temperature up to 150 °C at a distance higher than 10-20 m from the radiating well, limiting, at the same time, the maximum temperature reached in the well to values below 350 °C, in order to preserve the completion equipment.

For this purpose a wide spectrum parametric analysis was carried out. The studied parameters and their ranges of variation are reported in Table 1.

The model was implemented in COMSOL Multiphysics. User-defined equations were introduced through the partial differential equation (PDE) interface. Matlab scripts and Matlab-COMSOL interface were used to run the simulations, to configure parametric analysis and to post-process data.

Table 1: Range of RF system and tight shell parameters analysed in the numerical study.

Parameter	Range value [units]
Irradiation time	t = 0-2000 [d]
Antenna irradiated power	P_0 = 50-500 [kW]
Transmitted frequency	f = 1-3000 [MHz]
Tight Shell radius	R_{shell} = 0-5 [m]
Tight shell material loss tangent	tg(δ)shell = 10^{-3} - 10^{-4}

3. Results

All the results reported in the following refer to a reservoir with connate water boiling temperature of 160 °C, corresponding approximately to a pressure of 6 bar, typical of shallow reservoirs.

The thermal profiles reported in left graph of Figure 3 were obtained through simulations referring to a classic configuration, without the use of the tight shell. An emitted power of 200 kW is considered, at a frequency of 10 MHz. For each profile, two regions can be identified: a first region, near the well, where all the water is evaporated, and a second one, which begins after the temperature becomes lower than 160 °C, where water saturation is still close to the initial value.

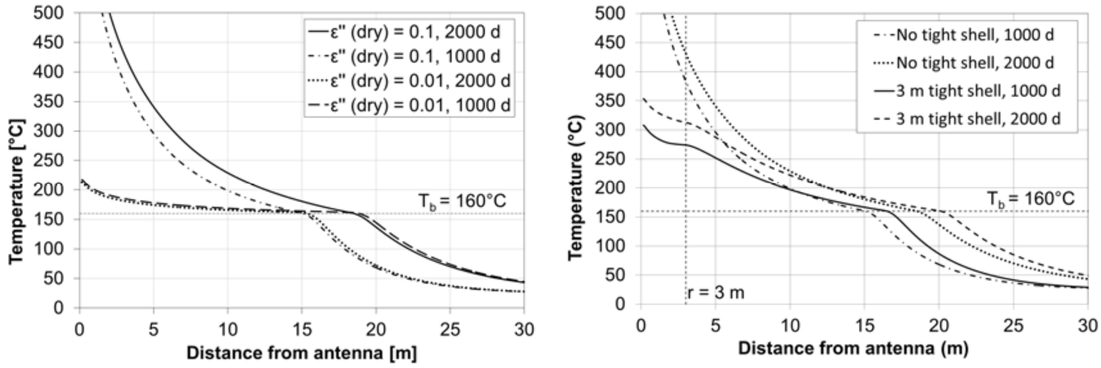

Figure 3: Simulation results. Left: comparison between thermal profiles obtained varying the dielectric properties of dried reservoir material without the use of the tight shell (f = 10 MHz, emitted power = 200 kW). Right: comparison between thermal profiles obtained without the use of the tight shell and with a 3 m radius tight shell (ε''(dry) = 0.1, tg(δ)(shell) = 10^{-3}, f = 10 MHz, emitted power = 200 kW).

Two cases are compared: one where the dried reservoir is quite lossy (ε'' = 0.1) and one where it is practically transparent to EM waves (ε'' = 0.01), in agreement with the values measured on oil sand samples. In the latter situation, noteworthy the temperature at the well is below 220 °C even for long irradiation times, and the reservoir heating is extremely uniform, since the dried material absorbs moderate amounts of EM energy.

In the case of the lossy reservoir material, on the contrary, the temperature at the well reaches really high values (well above 500 °C) and the resulting heating is far from uniform, with much of the energy dissipated in the region surrounding the well. The same condition would be obtained even for low-loss dried reservoir in the case of high reservoir pressure, giving high water boiling temperature and the absence of massive water evaporation.

These observation suggests that the classic configuration of the RF system can be suitable to heat uniformly low-loss shallow reservoirs, while if the dried material is still significantly dissipative or if the reservoir is very deep (so that the pressure is high and connate water evaporates at really high temperatures) this technique leads to an excessive temperature increase nearby the well, with the associated risk of damaging well completion equipment, and to a limited extension of the heated zone.

The tight-shell concept was introduced in order to overcome these limitations: in the right graph of Figure 3, the classic configuration is compared with one having a 3 m radius tight shell (with tg(δ) = 10^{-3}) around the radiating element. The reservoir is lossy (ε'' = 0.1 when dried), and frequency and power are again respectively 10 MHz and 200 kW. The effect of the tight shell is remarkable: the temperature at the well decreases of about 500 °C, and the radius of the volume heated over connate water boiling point increases of over 3 m, due to the improved energy distribution.

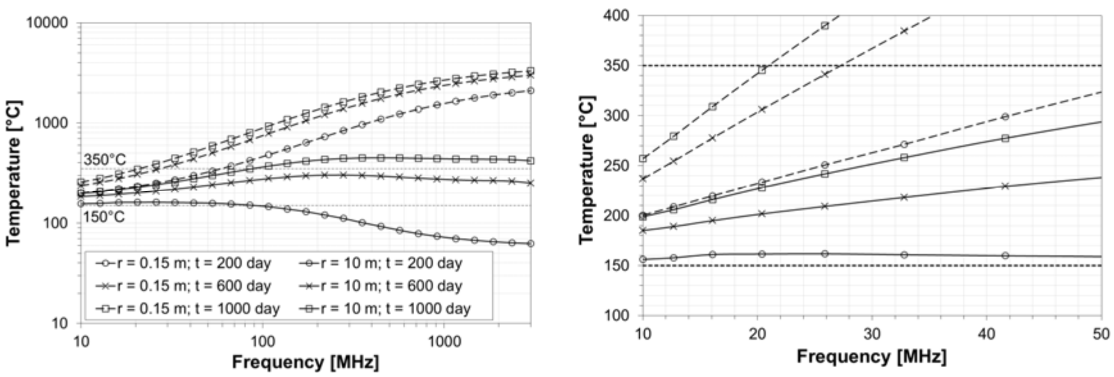

Figure 4: Frequency-temperature analysis for 200 kW irradiated power, 3 m radius tight-shell (tg(δ) = 10^{-3}). The diagram shows the temperatures reached at 10 m distance from the radiating well (solid lines) and near the wellbore (spotted lines) for different irradiation times, as a function of the transmitted frequency (in the range 10-3000 MHz). On the right, the range 10-50 MHz is zoomed.

Noteworthy the value of tg(δ) assumed does not require an extremely transparent material; for instance, several materials (such as natural quartz sands or proppants) measured by Sarri et al. (2012) show similar dielectric properties. In Figure 4, the results of a frequency analysis is reported, in terms of temperature reached at 15 cm and 10 m from the axis of the radiating element after 200, 600 and 1000 d of irradiation. Again, the power emitted is 200 kW, the dried reservoir material is low-lossy (ε'' = 0.01), and a 3 m radius tight shell with tg(δ) = 10^{-3} is considered. The best irradiation frequencies turn out to be those in the 10-20 MHz range. Higher frequencies are as well capable to heat deep into the reservoir, but the temperature at the wellbore results too high.

4. Conclusion

The paper shows the numerical modelling carried out in order to assess the feasibility of a novel method for unconventional oil thermal recovery, which involves the irradiation of the reservoir from a downhole antenna with electromagnetic energy in the RF range and in the presence of a tight shell made of a sufficiently low-loss material surrounding the antenna. The study was carried out using experimental data on thermal and dielectric properties of reservoir and well completion materials, and considering the heating requirements of a real oil sand reservoir, which needs to be heated up to at least 100-150 °C in order to make the bitumen sufficiently mobile to be extracted. The developed model is extremely simple (spherical geometry, static condition) in order to allow a fast assessment of the many parameters involved, namely irradiation frequency and power, material properties, system geometry.

Numerical study results are promising and demonstrate that a uniform heating of a considerable volume of reservoir can be achieved by a single radiating antenna. A proper system design and choice of RF operating parameters is mandatory to allow the uniform heating of large volumes of reservoir.

In particular, frequencies in the 10-20 MHz, coupled with the use of the tight shell, provide an effective solution to avoid the risk of high peak temperature at the radiating well, which can induce serious problems for well completion and electromagnetic system materials. The possibility to keep down well temperatures can allow to operate a long term, continuous RF process, needed to achieve high productivity. The use of a tight shell makes also the method much less sensitive to the dielectric properties of the reservoir materials (mainly porous solid matrix and hydrocarbons), making this technique an interesting alternative to steam- based methods for different kinds of unconventional oil resources.

Currently, further investigations are focusing on the development of a 3D, coupled electromagnetic, thermal, and fluid dynamic model, aiming to evaluate the effect of parameters such as the geometry and size of the tight shell, reservoir and oil properties, well positioning, production strategies.

References

Bientinesi M., Petarca L., Cerutti A., Bandinelli M., De Simoni M., Manotti M., Maddinelli G., 2013, A new technique for heavy oil recovery based on electromagnetic heating: pilot scale experimental validation, Chemical Engineering Transactions, in Press

Carrizales M.A., Lake L.W, Johns R.T., 2008, Production improvement of heavy-oil recovery by using electromagnetic heating, SPE Annual Technical Conference and Exhibition, Denver, Colorado, USA, DOI: 10.2118/115723-MS.

Kasevich R.S., Price S.L., Faust D.L., 1994, Pilot testing of a radio frequency heating system for enhanced oil recovery from diatomaceous earth, SPE Annual Technical Conference and Exhibition, New Orleans, Louisiana, USA, DOI: 10.2118/28619-MS.

Ovalles C., Fonseca A., Lara A., Alvarado V., Urrecheaga K., Ranson A., Mendoza H., 2002, Opportunities of Downhole Dielectric Heating in Venezuela: Three Case Studies Involving Medium, Heavy and Extra-Heavy Crude Oil Reservoirs, SPE International Thermal Operations and Heavy Oil Symposium and International Horizontal Well Technology Conference, Calgary, Alberta, Canada, DOI: 10.2118/78980-MS.

Sahni A., Kumar M., Knapp R.B., 2000, Electromagnetic Heating Methods for Heavy Oil Reservoirs, SPE/AAPG, Western Regional Meeting, Long Beach, CA, USA, DOI: 10.2118/62550-MS.

Sarri A., Batisti M., Bientinesi M., 2012, Measurements of Complex Permittivity of Geological Materials Mixtures at RF Frequencies, 6th European Conference on Antennas and Propagation (EUCAP), 26-30 March 2012, Prague, Czech Republic, 2109-2113, DOI: 10.1109/EuCAP.2012.6205920.

Sresty G., Dev H., Snow R.H., Bridges J.E., 1986, Recovery of bitumen from oil sands deposits with the radio frequency process, SPE Reservoir Eng. 1(1), 85-94.

Von Hippel R., 1966, Dielectrics and waves, M.I.T. Press, Cambridge, Massachusetts, USA.