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Radio Frequency heating for oil recovery and soil remediation

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Abstract: The paper presents basic principles of RF heating and describes its possible applications for oil extraction and soil remediation, based on the experience obtained by several years of work at Consorzio Polo Tecnologico Magona (CPTM). Activities include a complete approach, which goes through the steps of problem formulation, modeling, and experimentation. It is shown that RF heating can represent a valid alternative to more consolidated techniques for application to oil extraction from oil sand or heavy oil reservoirs and for organic polluted soil remediation, in terms of performances and operational flexibility. In particular, radiofrequency heating can be used in several scenarios where the use of alternative methods (such as steam injection) is not possible or strongly limited by geological or logistic constraints.

Keyword: Radiofrequency heating, Oil sand, Soil remediation, Enhanced Oil Recovery, Microwaves, Dielectric heating, Electrical

1. INTRODUCTION

The irradiation from downhole antennas with Radio Frequency (RF) electromagnetic waves is known since decades to be an effective technique to heat large portion of subsurface soils. Applications are known particularly in the oil extraction sector and in the soil remediation sector. The commercial development of this technique is still not complete, although researchers have been studying it for decades.

In this paper, we describe the major researches in both fields and outline advantages and limitations with respect to competing techniques. In particular, in Section 2 Radio Frequency heating is briefly introduced from the theoretical point of view and the dielectric properties of materials of interest are briefly reviewed. The following sections refer to activities carried on in the last years at “Consorzio Polo Tecnologico Magona”, a research center for innovation and technological transfer to the industries in cooperation con the University of Pisa. In particular, Section 3 focuses on the application of RF heating for oil enhanced recovery, while Section 4 treats its use for soil remediation. A general conclusion and some perspectives are given in Section 5.

2. RADIO FREQUENCY HEATING

1.1 Principles of radio frequency heating

Radio frequency (RF) refers to electromagnetic (EM) waves ranging from 500 kHz to 500 MHz. The principle of EM heating, in the RF field as well as in the microwave range, involves the conversion of EM energy into thermal energy through the interaction between the electromagnetic field and atoms or molecules present in the irradiated material. This interaction depends both on the nature of the material and on the radiation frequency (Daniel et al., 1999). Heating can arise from conduction losses, dielectric losses, and more rarely magnetic losses. The physical property associated with conduction losses is the electrical conductivity (σ), while the dielectric behavior of a material is described through its complex permittivity:

$$\varepsilon^* = \varepsilon_0 (\varepsilon' - j\varepsilon'') \tag{1}$$

where ε_0 is the permittivity of free space (8.85x10^{-12} F/m), and ε' and ε'' respectively the relative real and imaginary permittivity (or dielectric constant). Lossless materials have a negligible imaginary permittivity (insulators materials), while lossy materials have a significant imaginary permittivity. Since usually dielectric and conductive losses are present in the same material, an effective imaginary permittivity can be used:

$$\varepsilon''_{eff} = \varepsilon'' + \sigma / \omega \varepsilon_0 \tag{2}$$

where ω (=2πf) is the angular frequency. The heat generated in a unit volume of irradiated media can be calculated through the following formula

$$q = \omega \varepsilon_0 \varepsilon''_{eff} |E|^2 \tag{3}$$

where $|E|$ is the magnitude of the applied electric field.

The dielectric properties of materials vary with frequency and temperature. Moreover, the nature of an irradiated media can change during heating: a notable example is the loss of water of an irradiated soil when its temperature approaches the water boiling point. Given the highly lossy nature of water, the loss factor of the soil decrease significantly and often dramatically when its moisture content decrease.

1.2 Dielectric properties of oil reservoir and soil materials

Reservoir and soil materials are heterogeneous mixtures of solid materials (soil particles, which can be composed by different mineral species and characterized by different granulometry and porosity), liquid hydrocarbons, connate water and gas.

Several authors measured the dielectric properties of sands (Epov et al., 2009, Sarri et al., 2012) in the RF frequency band. They all agree about the real permittivity being practically constant with frequency, with values ranging from 2.5 to 5 in dependence of sand composition and morphology. The imaginary permittivity is constant with frequency as well, but with a larger variability (from 0.02 up to 2 for different authors). Values for limestone (Singh et al., 1980) vary between 3 and 5 for ε' and between 0.012-0.05 for ε'', while for sandstone (Singh et al., 1980, Saltas et al., 2005) much larger values were measured (from 5 to 30 for ε', from 0.03 to 0.75 for ε'').

Oils are generally non-dispersive, thus characterized by a real permittivity constant with frequency and in the range 2-3 and an imaginary permittivity in the range 0.02-0.05 (Epov et al., 2009). Anyway, exceptions exist: Saraev et al. (2007) measured an oil with a resonance phenomenon at frequencies around 300 MHz, while Kovalyova & Khaydar (2004) found a similar resonance for another oil but at a much lower frequency (around 1 MHz).

Water is always present in oil reservoir and in soils. It can constitute the wetting or non-wetting phase and can contain salts in different amounts and compositions, giving connate water a large spectrum of possible electrical conductivity values, which, according to (2) turn into different values of permittivity.

The permittivity of composite materials can be directly measured or calculated using mixing models, with different levels of accuracy. A popular model for soil is the Generalized Refractive Mixing Dielectric Model (GRMDM), described by Mironov et al. (2004), which use the volumetric fraction of the different components of the soil to calculate the mixture permittivity from the permittivity of single components. Models and measures show that the presence of water has a really significant impact on the mixture permittivity in the RF range and thus on the behavior of the material during radio frequency heating operations. As a way of example, in Fig. 1 we show the permittivity of an oil sand sample measured at different temperatures. After an increase of both the real and imaginary permittivity from 20°C to 50°C, a sharp decrease of both parameters is obtained once the boiling point of water is reached and thus water is evacuated from the sample. After that, the sample is able to absorb far less electromagnetic energy under the same electromagnetic field intensity. Since radiofrequency heating is a transient process, with the temperature of the irradiated soil continuously changing, it is fundamental to know how the soil permittivity varies with temperature and soil composition, and to design the system in agreement with this continuous variations.

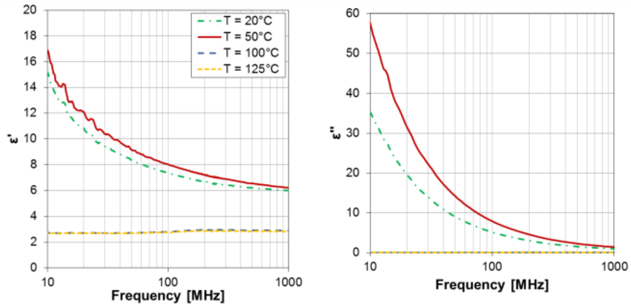

Fig. 1. Permittivity of oil sand sample with initial composition: 10% oil, 4.2% water, 85.8% quartz sand by weight at different temperatures (Sarri et al., 2012, Bientinesi et al., 2013).

3. RF HEATING FOR OIL EXTRACTION

In the last decades, oil & gas companies have been driven towards the research and exploitation of unconventional resources such as oil sand, oil shale, and heavy and extra-heavy oil by the decrease of the conventional oil reserves and by the increase in oil price. Unconventional oils have higher density and viscosity with respect to conventional oils, and are thus more difficult to extract, requiring Enhanced Oil Recovery (EOR) techniques, and to convert into marketable products, requiring additional upgrading processes (Clark, 2007). Alongside with mining operations for Canadian oil sands, thermal EOR methods are the more applied worldwide, in particular those involving steam injection into the reservoir to reduce oil viscosity. These methods require large amounts of fresh water and cannot be used for deep or very shallow reservoirs. Moreover, their effectiveness depends on reservoir geological properties. For example, in thin payzones steam injection can turn out to be scarcely effective or completely uneconomical. Thus, alternative ways to put energy inside oil reservoirs were studied. Electromagnetic (EM) irradiation from downhole antennas can overcome some limitations of steam injection, being less affected by formation geology and payzone depth and thickness, and requiring extremely compact equipment. Tens of patents have been registered since 1950s, but really few lab-scale or pilot data were published, and up to now, no commercial application was developed. This is mainly due to the many technical challenges involved in the integration of the electromagnetic system with the oil well system, which requires significant investments.

3.2 Applications of RF heating for oil extraction

The first patent in the field of oil reservoir RF heating was registered in 1956 (Ritchey, 1956). It described the irradiation of the reservoir from an antenna installed inside an extraction well at the payzone level, with a coaxial line for the transmission of radio waves from the surface (where they are generated) to the antenna; the frequency was in the range 0.5 MHz - 1 GHz. Several other patents published in the following decades (prominent examples are Kasevich et al., 1979, Sresty et al., 1984, Haagensen, 1986, Kasevich, 2007) introduced several modifications to this concept, allowing us to classify the different methods according to applied frequency (radiofrequency range or microwave range), well design (a unique well for irradiation and extraction versus distinct wells), field design (single isolated well versus well array), well direction (vertical, horizontal, or hybrid solutions). Some authors also theorized the coupling of RF irradiation with other techniques such as steam flooding (Supernaw & Savage, 1992) or supercritical CO_2 injection (Considine et al., 2007), in order to overcome some limitations of the single techniques.

Early lab-scale experimentations (Sresty et al., 1986, Kasevich et al., 1994, 3.2.1.3 Hu et al., 1999) demonstrated the possibility of heating up reservoir materials well above water boiling temperature by applying RF irradiation, and studied the effect on the temperature increase rate and on the oil recovery of factors such as temperature, pressure, connate water salinity, and solvent injection. Lab-scale experimentations suffer from the impossibility to scale down geometrically the irradiation process, since electromagnetic irradiation at RF frequency is characterized by very long wavelengths, incompatible with small volume tests, while by changing the frequency, both reservoir permittivity and temperature profile change abruptly.

Thus, field experiments are necessary for the experimental determination of the temperature profiles arising from RF downhole irradiation, but really few data are available, due to the high costs associated. The more significant experiences remain that of Sresty et al. (1986) and that of Kasevich et al. (1994). Sresty et al. (1986) tested a radiation system constituted by an interred triplet line with maximum power of 75 kW in a 25 m^3 oil sand deposit. The system worked at 2.3 MHz until complete water evaporation, taking place at about 120°C; then, given the decrease in the reservoir permittivity and hence the decrease in temperature rising rate, the frequency was increased to 13.6 MHz, reaching a final temperature of about 200°C after 14 days and recovering about 35% of the oil initially in place without any additional driving force apart gravity. The work by Kasevich et al. (1994) involves an irradiation system constituted by a RF generator with 25 kW power transmitting electromagnetic waves to a downhole antenna through a coaxial line. The antenna is installed into a well at a depth of 230 m. Unfortunately, the only available data are measured by a temperature probe at a distance of 3 m from the antenna. However, the recorded temperature showed an asymptotic trend, with the temperature increase rate slowly decreasing and approaching zero when the temperature approached the boiling temperature of connate water, after about 2 days of irradiation. This data confirms the formation of a dried zone near the antenna, where energy density is higher, once the temperature reaches water boiling point; this zone grows during irradiation, causing the electromagnetic energy to penetrate deeper in the reservoir. Kasevich et al. (1994) were the first authors to outline the importance of water evaporation (and thus of reservoir pressure, which determines water boiling point) in establishing the temperature profiles arising from RF irradiation. Further details on this subject are given in the next paragraph.

3.3 Experiences at CPTM

Consorzio Polo Tecnologico Magona, together with IDS and ENI, studied the RF heating of oil reservoir through several steps: oil sand material physical, chemical, and dielectric characterization; electromagnetic/thermal modelling; conceptual design of a new irradiation method and individuation of optimal parameters; validation of the method through pilot-scale testing. The general aim of the work was to define a method capable of heating from a downhole RF antenna the largest possible portion of reservoir while maintaining the temperature at the well at a temperature level compatible with well completion materials. This last problem is rarely taken into account, but it is of fundamental importance for several reasons. First of all, casing material in the section hosting the antenna must be transparent to EM waves, i.e. non-metallic; materials such as plastics and fiberglass have limited maximum operating temperatures. Moreover, excessive temperature can cause the oil to reacts forming heavy deposits that can adversely affect the oil flux. This maximum temperature can be variable depending on the used materials and on the well design, but can be placed between 150°C and 250°C. The modelling, described in detail in Bientinesi et al. (2013), allowed us to understand that, in many situations, the choice of the optimal frequency and power are not sufficient to guarantee a safe and effective heating of the reservoir. Two possible situations are described in Fig. 2, referring to a reservoir with a pressure of 6 bar, corresponding to a boiling temperature of connate water of about 160°C, and to 200 kW of RF power at 10 MHz.

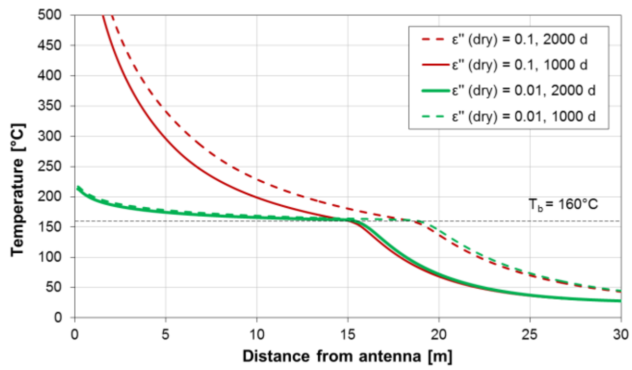

Fig. 2. Comparison between thermal profiles obtained varying the dielectric properties of dried reservoir material (f = 10 MHz, emitted power = 200 kW).

For each temperature profile, we can individuate a region, near to the antenna, where all water is evaporated, and RF power absorption decreased, and a second region where temperature is still lower than 160°C, water is still present, and permittivity is higher. Two different situation are compared: in one case, the dried reservoir material is quite lossy (ε'' = 0.1), in the other it is practically transparent to EM waves (ε'' = 0.01). In the latter situation, the temperature at the well remains at an acceptable level for very long irradiation times; for a lossy reservoir, on the contrary, temperatures continuously increase up to a level well over the maximum allowable temperature. In a real situation, when installing an antenna into a downhole well, it is impossible to know certain values for the permittivity of the materials surrounding the antenna, and thus the risk of overheating due to dishomogeneities is always present, and the beneficial effect of water vaporization can be not sufficient. Starting from these consideration, we found a possible solution by introducing, around the well in correspondence of the radiating antenna, a shell composed of material with extremely low imaginary permittivity. Such shell could be realized with under reaming techniques (up to maximum 1 m of diameter) or by injecting in the reservoir appropriate materials. As shown in Fig. 3, such shell would be capable of lowering the temperature at the well of several hundreds of degrees Celsius. Moreover, noteworthy the dried zone in the tight shell scenario is 3 m larger: thus, this structure is useful also to improve energy penetration and heating uniformity.

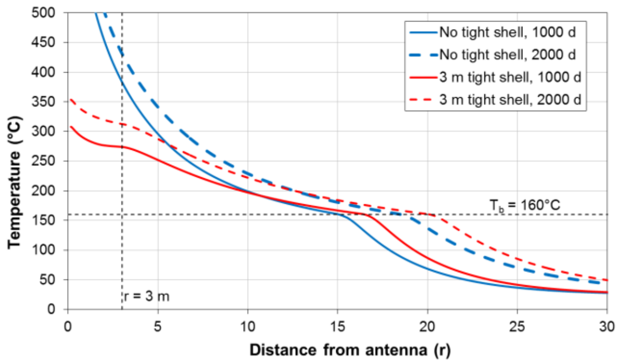

Fig. 3. Comparison between thermal profiles obtained with and without a 3 m diameter tight shell for a lossy reservoir.

CPTM designed and realized a pilot test (Fig. 4) irradiating from a dipole antenna about 2000 kg of oil sand inserted in a sandbox. The radiation frequency was 2.45 MHz, since lower frequency would have required much larger samples, and the emitted power 2 kW (Bientinesi et al., 2013). The antenna is surrounded by a cylindrical shell made of low lossy dry quartz sand. Temperature profiles were recorded throughout the test by optical fiber probes. The result are shown in Fig. 5.

Fig. 4. Oil sand irradiation pilot test .

We can observe that the temperature in the quartz sand shell is always lower than the temperature in the adjacent oil sand, demonstrating the effectiveness of the shell in preserving the antenna from high temperature. Water evaporation effect is also visible, since once the boiling temperature (100°C) is reached near the antenna, more microwaves penetrates deeper in the oil sand mass and temperature profiles become flatter. Experimental results were compared with a model adapted from that used for the simulations of Fig. 2 and Fig. 3, showing a really good agreement and thus confirming the assumptions of the model.

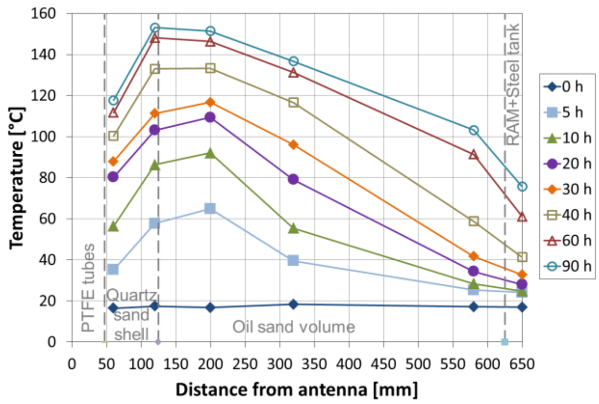

Fig. 5. Pilot test experimental results.

4. RF HEATING FOR SOIL REMEDIATION

The technique denominated In Situ Radio Frequency Heating (ISRFH) applied to the remediation of soils contaminated by hydrocarbons was developed starting from the technique conceived for oil extraction and described in section 3. The main difference is that, while for oil extraction typical depth of hundreds of meters must be reached, for soil remediation usually the polluted soil is collocated at few meters under the soil level. This difference implies important technological simplifications and a much higher efficiency in the transmission of electromagnetic waves from the surface, where they are generated, to the downhole antenna, where they are emitted into the soil. With respect to other thermally enhanced remediation techniques such as steam injection, resistive heating or conductive heating, ISRFH has two main advantages (EPA, 1997): the heating rate is much higher and the temperature profiles more uniform, independently from soil geology; and there is no fluid injected into the polluted soil, and thus the risk to enlarge the contamination to surrounding areas is minimized.

4.1 Applications of RF heating for soil remediation

Some pilot scale and full scale experimentations for ISRFH remediation were conducted in the past years. In all cases, RF heating was coupled with Soil Vapor Extraction (SVE) in order to remove the devolatilized organic pollutants. However, several difference among the tests could be observed. Jarosch et al. (1994) describe a test performed with an antenna inserted in a horizontal well through a clay vadose zone contaminated with chlorinated solvents. Operating conditions were power 25 kW and frequency 13.56 MHz, and the irradiation went on for 1 month, leading to temperatures in the range 60-130°C. About 170 kg of chlorinated solvents were extracted from about 800 m^3 of soil, with a 10-fold increase in the removal rate. The test described by Daniel et al. (2000) was performed with two antennas (27.56 MHz, 15 kW) irradiating in a vadose zone polluted with Diesel Range Organic compounds (DRO). The area, with a volume of about 100 m^3, was irradiated for 3 months, temperatures up to 340°C were reached and it was estimated that over 60% of DRO were removed. Roland et al. (2007) describe two experiments. In the first, the soil under a former organic solvent storage site was irradiated through an electrode array (2 MHz, 6.5-11 kW). The irradiation was on for one month, allowing to reach temperatures around 100°C, and the removal of BTEX via SVE was estimated to increase by a factor of 2-10. In the second experiment, they performed a short (2 h) test using a 5 kW, 13.56 MHz antenna in an horizontal well to heat up to 40°C the soil under a former petrol station; the flux of contaminant (BTEX, alkanes) removed via thermodesorption augmented by a factor of 8. The test described by CL:AIRE (2011) was performed at a former petrol station, with subsoil polluted with hydrocarbons. Three vertical antennas were used (13.56 MHz, 24 kW) in a volume of 480 m^3 of soil. The irradiation proceeded for 4 months, and the temperature reached were in the 45-95°C range; SVE extraction of VOCs increased by a factor of 12, and 945 kg of VOCs were eventually removed, corresponding to a removal yield of about 95% for BTEX and C8-C10 and of 80% for C10-C16 and C16-C35. Kasevich et al. (2012) used 4 antenna in 4 vertical wells (20 kW, 27.12 MHz) into a saturated soil containing 1,1,1-trichloroethane (TCA), trapped in ganglia structures, from where it is not recoverable by mobilization. The objective of the treatment is to increase the temperature in the area (70 m^2) up to 40-50°C, favoring the degradation by hydrolysis of TCA and the volatilization of the products, removed through SVE. The treatment lasted 36 months and allowed the removal of 65 kg of VOC and a 99% decrease in TCA concentration in groundwater in the target area.

All the previous examples show that ISRFH coupled with SVE can be used in a variety of different geological conditions, with different pollutants and temperature targets, and always leads to an increase in the contaminants removal rate with respect to SVE alone, and thus to a strong reduction of the remediation time. Moreover, with respect to other thermal technique, ISRFH has shown a higher flexibility and capability to be operated safely in difficult logistic conditions (for instance, beneath buildings). On the other hand, the costs of ISRFH have up to now limited its commercial development. It is difficult to evaluate a standard cost, since each site requires a specific design leading to different capital and operating cost. Anyway Daniel et al. (2000) reported cost ranging from 182 $/$m^3$ to 288 $/$m^3$, while CL:AIRE (2011) estimated 300 $/$m^3$. This values, though high, are much lower than the costs involved in the excavation and disposal of the contaminated soil in a landfill. In the next future, governments all over the world could increase the pressure on companies about environmentally impacted industrial sites, and ISRFH could be an important option for ambitious remediation programs.

4.2 Experiences at CPTM

In the past years, CPTM conducted different activities on ISRFH applied to the remediation of polluted soils.

A lab-scale experimentation was conducted, in order to evaluate the influence of dielectric heating (at microwave frequencies) on the desorption of organic pollutants from soils (Cioni & Petarca, 2011). Results confirmed the importance of the moisture content of soil in order to have higher heating rates and higher final temperatures, but showed also that, initial moisture content and power being equal, higher removal are obtained for contaminants with higher electrical permittivity in comparison to contaminants with similar volatility but lower permittivity. For all the tested organic contaminants (with boiling points up to 260°C), removal over 99% were reached within 15 min, with an initial water content of 0.15 kg per kg of soil and a maximum temperature of about 140°C, at a power density of 1956 W per kg of dry soil.

CPTM then designed for a real case (a soil polluted with chlorinated solvents, details are covered by a confidentiality agreement) an ISRFH/SVE treatment and calculated the associated costs. The polluted area is a square with side length of about 50 m, and the contamination is confined into a saturated zone with a thickness of about 4 m, giving a total volume of soil to be treated of 10000 m^3. Groundwater is flowing in the zone at an average rate of 0.5 m/day. Through electromagnetic and thermal modeling on different possible configurations, the optimal design was individuated. It involve the use of five 25 kW, 13.56 MHz antennas, inserted in parallel horizontal wells 2.5 m distant from each other. The total number of horizontal irradiation wells is 10 (see Fig. 6), and the 5 antennas are to be operated contemporarily in adjacent positions.

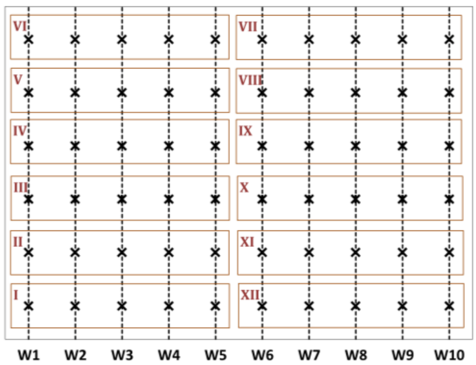

Fig. 6. Design of the ISRFH treatment by CPTM at a chlorinated solvents polluted site. The ten horizontal wells (W1…W10) are shown on the 50x50 m area, together with the 12 (I…XII) heating phases.

In each phase of the treatment, irradiation is programmed for 120 days, during which temperature of at least 80°C (with a maximum temperature at the well lower than 150°C) are reached in all the treated area; this temperature allows the desorption and volatilization of the chlorinated solvents, which are collected through SVE wells. After the end of the irradiation, antennas are moved in another position along the same wells, in order to heat an adjacent area. With a total of 12 phases of heating, as outlined in Fig.6, and a treatment time of 4 years, the entire area can be remediated completely. It was estimated that capital costs are 1.3 M$, while operating cost are 1.1 M$, for a total specific cost of about 140 $\$/m^3$. Capital costs are significantly lower than those from Daniel et al. (2000) and CL:AIRE (2011) thanks to the fact that the same antennas and RF generators are reused in different treatment phases. A pilot plant design preliminary to the remediation operation is currently ongoing.

5. CONCLUSIONS

The article reviews the main scientific literature about the use of radiofrequency heating in the oil extraction and soil remediation fields. Though studied for many years, this technique has not yet found commercial applications, but in the future the need to deploy non-conventional oil resources and the increase of the environmental sensitivity could give a new impulse to field experimentations.

For oil extraction, some technological barriers still exist. RF generators with high power (>100 kW) are expensive and not easily found on the market. Moreover, existent coaxial cables for RF waves transmission have power losses for meter that are quite high and a temperature rating somewhat too low for oil applications. Anyway, these technological problems could be solved if the demand of these items by oil companies will grow. Remediation applications, characterized by much lower depth and lower power levels, have been instead limited by the cost and by the availability of mature alternative technologies, but in several scenarios RF heating could offer important advantages that could lead to a real improvement of its application. CPTM in the past years gained experiences in both fields, thanks to projects involving modeling, lab-scale and pilot-scale experimentations, and design of real applications.

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