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A New Technique for Heavy Oil Recovery Based on Electromagnetic Heating: Pilot Scale Experimental Validation

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Due to the depletion and the increasingly high cost of conventional light oil resources, in the future unconventional oils are due to become one of the major hydrocarbon source. In order to extract crude oil from these resources, a sufficiently low viscosity must be achieved, for instance through temperature increase. Electromagnetic irradiation can be a suitable method for in situ heating of reservoirs: major problems connected with this technique are the extremely high temperatures that can be reached at the well and the strong dependence on local variations of reservoir material properties. These problems can be solved to a large extent by inserting around the well, in proximity of the radiating element, a tight shell made of low-loss dielectric materials. The experimental work described in this paper aims to study the phenomena connected with the electromagnetic heating of an oil sand reservoir up to 150 °C, in order to assess the effectiveness of the novel tight shell conceptual design. Over 2000 kg of oil sand were inserted in a steel box and irradiated at 2.45 GHz frequency. The radiating element is a dipolar antenna inserted in the center of the oil sand volume. The temperature in the oil sand was recorded throughout the test in several points, in order to estimate temperature profiles along the distance from the antenna.
Results confirm that electromagnetic irradiation is capable of heating both wet and dry oil sands, since the temperature in the sample rises well above connate water boiling temperature. Water vaporization significantly impacts on temperature profiles and contributes to limit the temperature near the well. An even larger positive effect on energy distribution and heating homogeneity is assured by the low-loss shell realized around the antenna, that is extremely efficient in lowering the temperature in this critical zone.

1. Introduction

Electromagnetic (EM) irradiation with Radio Frequency (RF) can be a sound alternative to classic thermal recovery methods for the extraction of heavy oil and bitumen from unconventional oil reservoirs. These methods are based on the injection of steam or other hot fluids in the reservoir, and cannot be applied in several occasion, for instance for very shallow or very deep reservoirs.
The placement of a downhole antenna in an oil producer well or in parallel wells has been prospected by several patents (examples are Ritchey, 1956, Haagensen, 1965, Kasevich et al., 1979, Bridges et al.,1979, Kiamanesh, 1992, Kasevich, 2008). On the other hand, really few experimental data were published to demonstrate the applicability of the technique (Sresty et al., 1986, Kasevich et al., 1994, Hu et al., 1999) and no author showed temperature profiles generated by RF irradiation.
Temperature profiles are indeed fundamental to assess the feasibility and efficiency of this technique, since one of the major problems arising from this configuration is the extremely high temperature that, depending on the dielectric properties of reservoir materials and on operating parameters such as reservoir pressure, can be reached in the wellbore surrounding. In order to overcome this limitation, a

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novel design of the radiating well was proposed and described in a parallel paper (Cerutti et al., 2013), and its effectiveness was assessed through a sensitivity analysis performed by means of a simplified numerical model. The main idea is to put around the well, at the height of the radiating element, a spherical or cylindrical tight-shell made of a low-loss dielectric material, in order to limit the absorption of EM energy in this zone, where the energy flux is maximum, and to allow more energy to travel towards the reservoir.
The aim of this work is to experimentally validate the observations derived from the simulation of RF heating in the presence of the tight-shell, and in particular to verify if such structure is capable of lowering the temperature reached near the well during irradiation.

2. Materials and Methods

In a parallel paper (Cerutti et al., 2013), frequencies in the range 10 - 20 MHz were individuated as optimal for this application. Anyway, an experimental test at such frequencies would require to operate directly on field, since the volume interested by the heating would be of several hundreds of cubic meters. We chose therefore to operate in the microwave range, at 2.45 GHz, since at this frequency the wavelength and the penetration depth of the radiation are much shorter and allow to scale down the volume of the experiment. A box filled with oil sand samples was prepared and irradiated through a dipolar antenna, and the temperature in several points inside the volume was measured and recorded.

2.1 Experimental set-up

Oil sand samples were reduced in cubic blocks (73 in total, for a total weight of about 2,200 kg) with side length 25 cm, by heating them at 70 °C and pressing the heated material into a mold. The oil sand volume is prepared by assembling the blocks into a steel containment tank (Figure 1), and has a square base with side length 1.25 m and is 0.75 m high. A vacant position was left in the center of the volume, in order to insert the antenna. For this purpose, two concentric PTFE tube were used: the inner is used for the insertion of the antenna, the outer (having external diameter 95 mm) is filled with silicon oil (Rhodorsil Oil 47 V20, Bluestar silicones). Outside this tube, a cylindrical shell with outer diameter of 250 mm was realized and filled with a low-loss quartz sand. A 0.2 mm thick PTFE sheet separates the shell from the outside, which is filled with oil sand. The base and the internal faces of the steel tank were covered with sheets of a Radar-Absorbent Material (RAM, Eccosorb SF2.5). This material is capable of absorbing all the microwaves reaching the metallic walls, which otherwise would be reflected by the metallic walls towards the oil sand volume.
A water-cooled magnetron, with a maximum output of 2 kW, fed by a switching power supply and controlled via PC, generates the microwaves. Downstream, an isolator blocks the reflected microwaves, and the reflected power is measured through a linear power sensor. Microwaves travel in a waveguide from the control room to the experiment room, then they are transferred in a rigid coaxial line through an adapter. The coaxial line terminates in the antenna, described in the section 2.2, situated in the center of the oil sand volume.
Several fiber optic temperature sensors are inserted into the oil sand volume and in the quartz sand shell, in order to monitor the heating process. K-type thermocouples are used to monitor the temperature of the steel tank, since no EM field is present outside the tank.

2.2 MW antenna

The specifications for the design of the antenna are:

- a maximum diameter of 60 mm;
- operating frequency 2.45 GHz;
- a maximum return loss of 10 dB;
- a radiation diagram optimized for power radial distribution.

A modelling tool developed by IDS (Ingegneria dei Sistemi) was used for the design.
The antenna, shown in Figure 1, is constituted by a rigid coaxial line with the inner conductor longer than the outer one, several circular elements terminating the inner conductor, and a mobile choke, used to decrease return currents and adjust the impedance.
The return loss of the realized antenna was measured using a Network Analyzer inside the experimental set-up, giving a value of -29 dB.

Figure 1: Experimental set up. Oil sands blocks placed in the steel containment tank (top-left); rigid coaxial line terminating in the dipolar antenna (top-right); close up image of the antenna inserted in the low-loss shell (bottom-left); comprehensive view of the set up (bottom-right).

2.3 Material properties

The oil sand samples used in the experiment were furnished by ENI. These samples, as well as the quartz sand used for the cylindrical shell, were characterized through a series of techniques described elsewhere (Sarri et al., 2012). Results are shown in Table 1 and Table 2.

The dielectric permittivity of oil sand is practically constant with temperature as long as water evaporation temperature is not reached. Once the connate water is evaporated, though, both the real and the imaginary part of permittivity decrease significantly (Table 1).

The quartz sand was chosen for two main reasons: it has a particularly low imaginary part of dielectric permittivity, giving no significant heat generation as required by the low-loss shell, and the real part is really similar to that of oil sand, minimizing the reflection of microwaves at the interface (Table 2).

Table 1: Physical and dielectric properties of oil sand used in the experimentation (Sarri et al., 2012).

Property		Value
Density		2,100 kg/m^3
Sand void grade		40%
Water content		0.25% wt.
Oil content		13% wt.
Dielectric constant	ε’	3.8
(2.45 GHz, 25 °C)	ε’’	0.1
Dielectric constant	ε’	2.5
(2.45 GHz, >100 °C)	ε’’	0.01
Specific heat (25 °C)		930 J/(kgK)
Thermal conductivity (25 °C)		0.93 W/(mK)

Table 2: Physical and dielectric properties of quartz sand used in the experimentation (Sarri et al., 2012).

Property		Value
Bulk density		1620 kg/m^3
Void grade		39.1%
Dielectric constant	ε'	2.9
(2.45 GHz, 25 °C)	ε''	0.001
Dielectric constant	ε'	2.5
(2.45 GHz, >100 °C)	ε''	0.01
Specific heat (25 °C)		800 J/(kgK)
Thermal conductivity (25 °C)		0.24 W/(mK)

2.4 Irradiation test

The properties of oil sand are due to change following its heating. In particular, the evaporation of the connate water leads to a decrease in oil sand permittivity. As a consequence, only a single test can be performed with the realized set-up.

The MW power was initially set at 1 kW. After a quasi-stationary temperature profile was reached, the power was increased to 1.5 kW after 29 h, and to 2 kW after 36.5 h. The test globally lasted over 12 days. The reflected power was continuously monitored and never exceeded 5 % of the emitted power.

The signals from fibre-optic sensors and thermocouples were recorded by a data logger with a frequency of 60 records per h, and the data were stored in a personal computer.

3. Results

Temperatures were mainly recorded on the horizontal plane which passes through the mid-section of the antenna. On this plane, the electromagnetic field is at its maximum, and decreases with increasing distance from the antenna.

In Figure 2, for instance, the temperature values measured by six sensors, placed on a horizontal straight line going from the mid-section of the antenna to the external wall of the steel tank, are reported. Each sensor is identified in the legend through its distance (r) from the antenna axis. Two vertical dotted lines identify the moments when the MW power was increased.

If the irradiated material had the same dielectric and thermal properties anywhere, the maximum temperature at any instant would be expected in the points nearest to the antenna, where the MW wave density is higher. Noteworthy the maximum temperatures are instead recorded not by the sensor at 60 mm, but by those at 120 and 200 mm, whose temperatures are practically coincident. Between these two points, and exactly at 125 mm from the antenna, lies the interface between the low-loss quartz sand shell and the oil sand material. This is a first evidence that the quartz shell absorbs a really small amount of EM energy, and its heating is mainly due to thermal conduction from the adjacent oil sand.

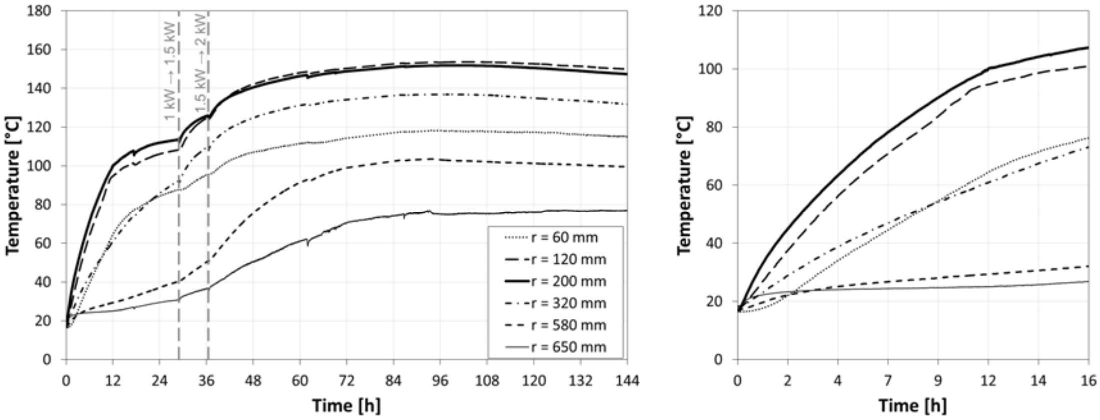

Figure 2: Experimental results. Temperature increase throughout the test at different distances (r) from the antenna at the height of the antenna mid-section. On the right, the graph is zoomed for the first 16 h of irradiation to show the effect of water evaporation from oil sand.

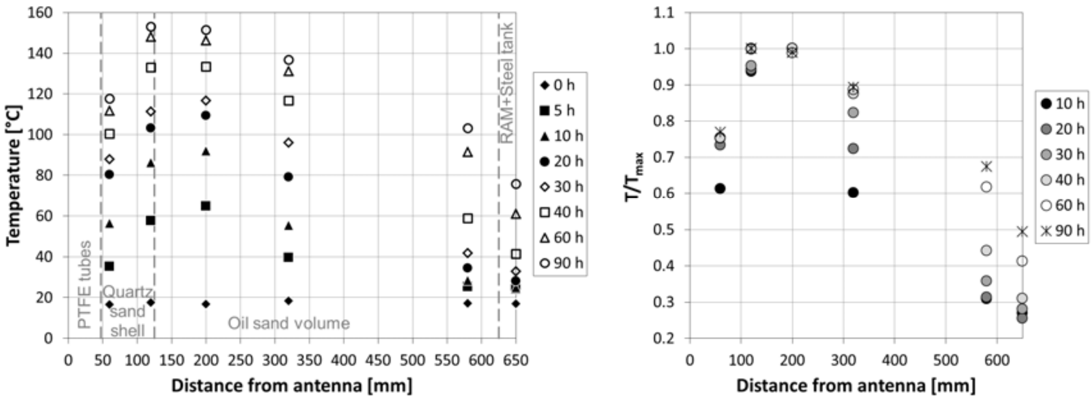

Figure 3: Experimental results. Temperature profiles at different irradiation times versus the distance from the antenna at the height of the antenna mid-section. Absolute (left) and normalized (right) temperatures.

Another interesting observation arises looking at the right side of Figure 2, where the same graph is zoomed for the first 16 h of irradiation, and specifically at the recording for r = 200. Once the temperature of 100 °C, corresponding to the water boiling point, is reached, the heating velocity significantly decreases. This effect is due to the reduction of the dielectric permittivity of oil sand after the connate water is evaporated (see Table 1). Noteworthy the sensor at r = 120 mm, which is placed in the quartz sand shell, shows a similar velocity decrease starting some tenth of minutes before, even if the temperature is lower than 95 °C and the quartz sand contains practically no water. This phenomenon confirms that the heating of the quartz sand shell is almost completely attributable at the thermal conduction from the warmer oil sand, heated by MW irradiation.

In Figure 3 the same experimental results are presented in terms of temperature profiles at different times along the distance from the antenna. The analysis of the left graph clearly shows how the presence of the quartz shell allows to maintain a moderate temperature near the antenna, while the maximum temperature is located somewhere in the oil sand near to the interface with the shell.

Again, even the effect of water evaporation is apparent, especially observing the right graph, where temperatures are normalized by dividing them per the maximum temperature in each profile. As long as the temperature is below 100 °C at any distance from the antenna (irradiation time below 20 h), the temperature profiles are really sharp, with the temperature around 125-200 mm from the antenna increasing rapidly while at longer distances the temperature increases more slowly. As water begins to evaporate, less energy is absorbed in the zones of oil sand nearest to the antenna and more and more MW energy is transmitted to farther areas. As a consequence, temperature profiles become gradually flatter.

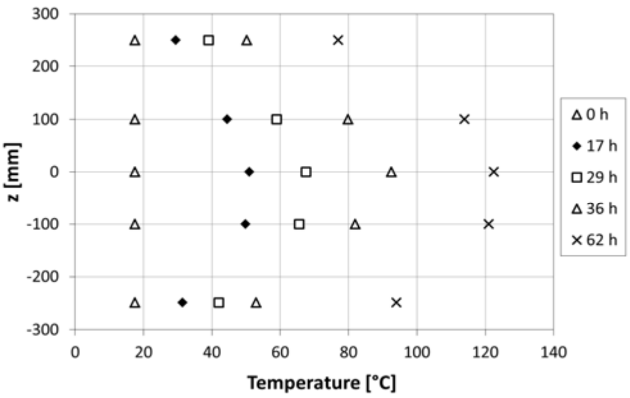

Figure 4: Experimental results. Temperature profiles for different irradiation times versus the vertical quote (z) at a distance of 390 mm from the antenna. The z = 0 reference is in correspondence of the antenna mid-section.

Figure 4 shows the vertical temperature profiles inside the oil sand volume at a distance of 390 mm from the antenna. The maximum temperature is always located on the antenna midsection, as expected, confirming the good radiation pattern from the MW antenna.
Temperature above the antenna mid-section tends to be lower than those under it at the same distance. This fact can be explained through the higher thermal dissipation on the top of the oil sand volume, which is exposed to air convection, with respect to the bottom.

4. Conclusions

This paper presents an experimental test aiming to assess the use of a low-loss dielectric shell placed around a downhole antenna for heavy oil thermal recovery. This novel technique could improve the applicability of RF heating for enhanced oil recovery, by lowering the temperature reached at the wellbore during irradiation and by making this method much less sensitive to local dielectric properties of the reservoir materials.
Experimental results clearly show that electromagnetic waves are capable of heating oil sand samples up to and above the connate water boiling temperature. Moreover, the low-loss shell turned out to be capable of lowering the temperature near the MW antenna and of better distributing the electromagnetic energy in the oil sand volume.
The effect of water vaporization was as well confirmed by the experimental results. In the regions where all water is evaporated (which are the regions closer to the radiating well), electromagnetic energy is poorly absorbed and the temperature rise is significantly slowed down, allowing more energy to be transmitted to the more distant regions. When assessing the possible application of RF heating to a particular reservoir, the role of reservoir pressure must therefore not be underestimated, since it determines water boiling temperature and eventually the shape of temperature profiles.

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