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Microwave-Assisted Heavy Oil Production: An Experimental Approach

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Conventional enhanced oil recovery (EOR) methods, such as steam injection, are usually not cost-effective for deep wells and wells produced from thin pay zones, because of excessive heat loss to the overburden. For such wells, minimizing heat losses can be achieved using microwave heating. In this study, the feasibility of this method was investigated. Heavy oil samples from conceptual reservoirs (Bati Raman, 9.5° API; Garzan, 12° API; and Camurlu, 18° API) in southeast Turkey were used. Using a novel graphite core holder packed with crushed limestone premixed with crude oil and water, effects of operational parameters, such as heating time and waiting period, as well as rock and fluid properties, such as porosity, permeability, wettability, salinity, and initial water saturation, were studied. It was found that high-salinity water promotes oil production during microwave-assisted production. High water saturations lead to higher oil productions regardless of the viscosity of the oil. It was finally concluded that microwave heating could be used to stimulate heavy oil production.

Introduction

Crude oils whose American Petroleum Institute (API) gravity is smaller than 20 are called heavy oil, which can be produced using thermal recovery techniques. In these techniques, heat is injected into the formation, which reduces the viscosity of the oil and results in a higher production rate.[1] Hot-fluid injection, *in situ* combustion, and thermal stimulation are the thermal recovery methods.[2] Microwave heating is a thermal stimulation method, and in the past, microwave radiation has been used in many areas of the petroleum industry.[3] Microwave irradiation applications include inspecting coiled tubing and line pipe,[4] as a treatment of wastewater/oil emulsion[5] and for saturation monitoring.[6] Microwaves are also used for monitoring phase behavior and measuring multiphase flow.[7,8] Furthermore, microwaves are used in various technological and scientific fields to heat dielectric and, on occasions, non-dielectric materials.[9,10] Thus, processes such as the drying and heating of minerals and inorganic products, the carbothermic reduction of metal oxides, mineral leaching, coal liquefaction, the production of active carbon, spent carbon regeneration, and the surface chemistry modification of carbons are only a few examples of the different processes currently being used or investigated.[11,12] Microwave heating has also been considered as an alternative for carrying out the pyrolysis of biomass,[13,14] coal,[15,16] oil shales,[17,18] and various

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organic wastes.[19,20] These materials are, in general, poor receptors of microwave energy; therefore, they cannot be heated directly to the high temperatures usually required to achieve total pyrolysis. However, microwave-induced pyrolysis is possible, if the raw material is mixed with an effective receptor of microwave energy, such as carbon[17,21] or certain metal oxides.[15,16] Microwave heating effectiveness depends upon several parameters, such as heating period, amount, and type of matter that will be subjected to the microwave irradiation, the cell material in which the matter will be placed.[22]

Several studies have been performed to study the application of microwave heating methods to heavy oil recovery. Cambon et al.[23] studied the Canadian tar sand for producing heavy oil by microwave heating techniques at 2450 MHz and reported up to 86% yield in distillable products, which is similar to those results obtained from conventional methods. Warren et al.[24] carried out a numerical simulation of microwave (915 MHz) heating of an aquifer drive Saskatchewan reservoir. The authors reported an increase in the cumulative oil produced by microwave heating (27%) in comparison to that calculated for cold production (18%). This increase was attributed to a higher oil/water mobility ratio and a reduction of water fingering as a result of the viscosity decrease. Ovalles et al.[25] studied three different conceptual reservoirs that contained a medium crude oil (24° API), a shallow (1100 ft) Lake Maracaibo heavy oil (11° API), and thin pay zone (20 ft) Orinoco Basin extra-heavy crude (7.7° API). Sensitivities to frequency and microwave power were obtained through numerical simulation. Simulation results showed a significant acceleration in the oil production because of microwave heating, which was then attributed to a reduction of crude viscosity, and the fact that the dielectric heating process can produce approximately 10 times more energy than it uses as electricity. Sahni et al.[26] performed numerical simulations of dielectric heating in both horizontal and vertical wells. Initially, the authors considered a steamflood process in addition to radio frequency (RF) and microwave heating and found better temperature distributions than those using steam alone.[27] Then, a 60 kW microwave antenna was placed 30 ft from a vertical producing well, and an 80% increase in cumulative oil was observed in relation to that calculated for cold production.

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While there are many studies that discuss the application of microwave heating to heavy oil reservoirs, the effects of initial oil saturation, wettability, and rock properties, such as porosity and permeability, are not discussed properly. Using a novel, microwave friendly graphite core holder packed with crushed limestone, effects of operational parameters, such as microwave heating time and waiting period, as well as rock and fluid properties, such as permeability, porosity, and initial water saturation, and the addition of metallic additives using a conventional microwave oven operating at 2450 MHz are studied for three heavy crude oils in unconsolidated porous media. Because microwave effectiveness depends upon the microwave power absorption coefficient and is directly related to the dielectric properties of the material, an analytical method developed is coupled with a least-squares minimization algorithm to obtain a microwave power absorption coefficient.

Theory

In a porous medium saturated with oil and water, the following takes place during microwave heating. Because oil and water have molecules that may have positive and negative particles, they tend to behave like microscopic magnets. As the positive half cycle of the microwave penetrates the porous medium, the negative particles of the molecules are attracted and attempt to align themselves with this positive field of energy. Then, when the microwave energy alternates to the negative half cycle, the opposite occurs: the negative particles are repelled, and the positive particles are attracted, causing a flipping motion (actually, this reaction is the movement of the particles within each molecule; therefore, technically, they reverse polarity). This might be compared to a room full of people trying to run back and forth from one side to the other. Obviously, there would be a lot of bumping, rubbing, agitation, and friction that results in heating of the porous medium and heat transfer.

Heat transfer from a microwave source to a porous medium can be described by the energy equation. Evolution of temperature as a result of microwave irradiation can be then obtained by the heat equation with the following modification:

$$\rho c_{\mathrm{p}} \frac{\partial T}{\partial t} + \rho_{\mathrm{f}} c_{\mathrm{p,f}} \vec{v}_{\mathrm{f}} \vec{\nabla} T = \vec{\nabla}(\lambda_{\mathrm{c}} \vec{\nabla} T) + P \tag{1}$$

where ρ, c_{p}, and λ_{c} are the density, specific heat capacity, and thermal conductivity of the medium, respectively, ρ_{f}, $c_{\mathrm{p,f}}$, and $\vec{v}_{\mathrm{f}}$ are the density, specific heat capacity, and superficial velocity of the fluid phase, respectively, and P is the electromagnetic dissipated power per unit of volume (P), based in Maxwell's equations, is a function of the electric field $\vec{E}$ and the effective electrical conductivity (σ) of the medium, and is represented by the following expression:

$$P = \frac{\sigma + \omega\varepsilon \tan \delta}{2} |\vec{E}|^2 \tag{2}$$

The energy efficiency of microwave heating is affected by the medium dielectric properties and their variations while heating. The electromagnetic heating process is directly related to the frequency (f) employed ($\omega = 2\pi f$). For the low frequencies ($\sigma \gg \omega\varepsilon \tan \delta$), ionic heating is dominant. For high-frequency cases ($\sigma \ll \omega\varepsilon \tan \delta$), dielectric heating is the main thermal process. In both cases, the dissipated power distribution and, consequently, the temperature behavior directly depend upon the electric field distribution that, in turn, depends upon the electromagnetic applicator used. For practical reasons, the applicator must radiate in all directions of the hydrocarbon medium surrounding the wellbore.

Assuming symmetry in radial homogeneous conducting medium, no heat losses to the adjacent formations and strictly radial pressure distribution electromagnetic radiation propagation will be absorbed following eq 3

$$\frac{d\Phi(r)}{dr} = -\left(\alpha + \frac{1}{r}\right)\Phi(r) \tag{3}$$

where $\Phi(r)$ is the power density (watts/cm^2) and α is the power absorption coefficient (cm^{-1}) that depends upon the physical properties of the absorbing medium in the following manner:[21]

$$\alpha = 0.02\sqrt{\left(\frac{\omega^2\mu\varepsilon}{2}\right)\left(\left(1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2\right)^{1/2} - 1\right)} \tag{4}$$

where σ is electrical conductivity (mho/m), μ is permeability (H/m), ε is permittivity (F/m), and ω is angular frequency [$2\pi \times$ frequency (f)]. We then define the total power radiated across the radius r for a cylinder of height h (m) as eq 5.

$$P(r) = 2\pi rh\Phi(r) \tag{5}$$

Differentiating eq 5 by r and solving it using eq 3 gives

$$P(r) = P_0 e^{-\alpha(r-r_0)} \tag{6}$$

If r_0 is the wellbore radius, then $P_0 = P(r_0)$ is the total power radiated. Combining this equation with the mass balance equation because of oil moving in and out of a cylindrical element at temperature $T(r)$ gives the following equation:

$$\frac{\partial T}{\partial t} = \frac{1}{2\pi rh\rho_t C_t}\left(\frac{\alpha P_0 e^{-\alpha(r-r_0)}}{4.18} + \rho_o q_o C_o \frac{\partial T}{\partial r}\right) \tag{7}$$

where C_t and C_o are the specific heat (cal g^{-1} °C^{-1}) of the total system and oil, respectively, q_o is oil flow rate (cc/s), and ρ_t and ρ_o are the total density (g/cc) and oil density, respectively, defined by eq 8

$$\rho_t C_t = \rho_r C_r(1-\phi) + \phi\rho_w C_w S_w + \rho_o C_o(1-S_w) \tag{8}$$

where subscripts o, w, and t refer to oil, water, and total, respectively, and S is saturation. Steady-state temperature distribution because of microwave radiation at constant oil production is then obtained as

$$T(r) = T_o + \frac{P_0 e^{-\alpha(r-r_0)}}{4.18\rho_o q_o C_o} \tag{9}$$

Transient temperature in the case of a constant oil flow to the wellbore is given by

$$T(r,t) = T_o + \frac{P_0 e^{\alpha r_0}}{4.18\rho_o q_o C_o}\left(e^{-\alpha r} - e^{-\alpha\sqrt{r^2+2At}}\right) \tag{10}$$

where

$$A = \frac{\rho_o q_o C_o}{2\pi h\rho_t C_t} \tag{11}$$

Finally, for the no flow case, taking the limit of eq 10 as the flow rate goes to zero gives the following result:

$$T(r,t) = T_o + \frac{\alpha t P_0 e^{-\alpha(r-r_0)}}{2\pi rh(4.18\rho_o C_o)} \tag{12}$$

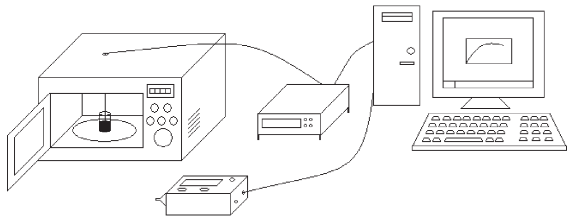

Figure 1. Experimental equipment.

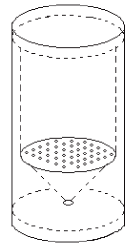

Figure 2. Core holder.

The mathematical model results indicate that the temperature increase is a linear function of the microwave power applied to the porous medium. High power absorption coefficients and light oils improve microwave heating and process performance. However, another important result is that P declines exponentially with distance, limiting the microwave heating process applicable around only a few feet of radius around the wellbore.

Materials and Methods

Equipment. A Vestel MD-GDX23A 1400 W microwave oven that operates at 2450 MHz with variable power and time settings was used during the microwave tests (Figure 1). A novel graphite core holder (5.2 cm diameter and 8.5 cm height) with a conical bottom section that houses a perforated graphite disk to allow for drainage of produced oil was used (Figure 2). The main advantage of the graphite core holder is that, as opposed to metallic core holders, it allows for penetration of microwave energy and resists high temperatures. A fiber optic thermocouple placed at the center of the graphite core holder and attached to a temperature reader and a personal computer through a hole at the top of the microwave oven enabled continuous temperature measurement. A fiber optic thermocouple is preferred because it is immune to electromagnetic and RF interference as opposed to classical thermocouples. It has an additional advantage of being corrosion-resistant. Viscosity measurements of crude oil before and after experiments were conducted using Brookefield and Haake viscometers. Specific and API gravities of crude oil were measured by a glass hydrometer.

Method. Heavy oils from three different conceptual heavy oil reservoirs located in southeast Turkey are used (Table 1). Both oils are heavy oils, with the exception of Garzan, which is a paraffinic crude oil. To create a porous medium, crushed carbonate samples are sieved with three different openings: 10−20, 20−50, and 80−160. Use of these sieves resulted in samples with three distinct porosities (25.86, 34.10, and 38.95%). The porosities were calculated using correlations for wet sandpacks presented by Beard and Weyl.[28] The mixing procedure changed according to the wettability type of sample. To create water-wet porous medium, deionized tap water was initially added to sand and mixed thoroughly and then oil was introduced to the resulting mixture to achieve the desired

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Table 1. Properties of Conceptual Heavy Oil Reservoirs

field	Bati Raman[30]	Camurlu[31]	Garzan[24]
lithology	limestone	limestone	limestone
reservoir temperature (°F)	150	115	179
reservoir pressure (psia)	1750	1700	2320
porosity (%)	18	21	6
permeability (md)	58	40	3
water saturation (%)	21	18	31
API gravity (deg)	13	12.2	18.5
specific gravity (g/cm^3)	0.9772	0.985	0.9433
viscosity at reservoir temperature (cp)	592	700	33
formation water salinity (ppm)	40000−160000	60000	3000−10000
original oil in place (10^6 STB)	1850.0	377.437	53.0

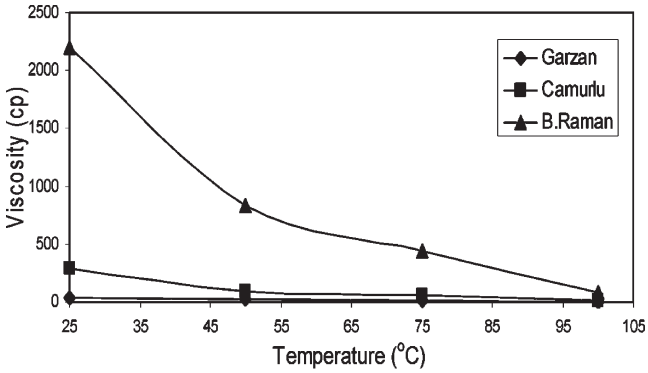

Figure 3. Viscosity variation with temperature.

saturation. Likewise, to create oil-wet porous medium, heavy oil was first added to sand, mixed thoroughly, and aged for about a week following a similar procedure proposed by Graue et al.[29] Water was then added to the mixture to reach the desired saturation. For mixed-wet samples, half of the mixture was prepared using the aforementioned oil aging procedure, while the other half was prepared with water. After aging a day long, the limestone−oil−water blend was mixed thoroughly in a bowl. Water is added to the samples by considering the formation salinities mentioned in Table 1. Representative water saturation values were 20, 40, and 60%, respectively. Viscosity variation of each crude oil with temperature is presented in Figure 3. To ensure that the sand has the same perfect wettability characteristics in every test, the model was refilled with fresh sand for each experiment. The empty model was positioned vertically, and the sand was poured into the model. Then, the model was gently tapped at both sides, to make the sand settle as tightly as possible. After placing a Teflon gasket on the top of the model, the other end piece was attached. This method of packing was found to lead to the most homogeneous sandpack that could be obtained. There exists, however, probably no perfect homogeneous sandpack, nor is it possible to produce exactly identical packs.

Experiments are initiated by setting the microwave oven at the maximum available power (900 W). Power applied in each experiment is changed such that, for continuous heating cases, the heating time is 180 s, whereas for heat and soak type experiments, the heating time is 30 or 60 s, followed by 180, 240, or 360 s soaking time repeated in 4 cycles. Oil and water productions are measured at the end of each experiment by weighing the oil collected at the conical section of the graphite core holder.

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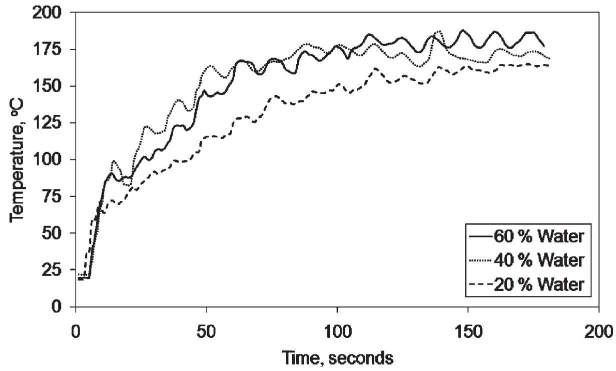

Figure 4. Temperature variations observed in water-wet porous media for Bati Raman crude oil with ϕ = 25.86%.

Results and Discussion

General Observations. Figure 4 shows temperature variations observed during experiments carried out with the Bati Raman crude at differing water saturations in water-wet porous medium. Temperature/time plots show a steady linear climb with a alternating trend up to a certain time, and then a change in slope is observed. This indicates that the water is vaporizing but the crude oil is still in the liquid phase. The change in slope occurs at different times for experiments with different initial water saturations. Initially, the reservoir model is saturated with the reservoir fluids, and hence, the microwaves are propagated through a continuous medium without any "breaks". As the temperature increases, oil becomes less viscous and, with the help of gravitational forces, moves down to the conical production chamber. Thus, voids are created, making it increasingly difficult for the weaker waves to propagate. Waves with higher electromagnetic frequencies are able to overcome these "breaks" better than the weaker ones and are able to penetrate into the partially saturated porous medium and, therefore, recover more oil. Because the total water present in the porous medium is different in each experiment, slight differences in packing flow paths (i.e., tortuosity) are somewhat different in each experiment. That is why a different time is required to reach a slope change in temperature−time plots. Moreover, because the number of liquid molecules that bump, rub, and agitate decrease as the water saturation decreases, the resulting heating energy decreases. Another important observation is the presence of cyclic increase and decrease of measured temperatures during an experiment. Because a commercial microwave oven does not continuously supply microwaves, a cyclic increase and decrease of temperature is observed. For the microwave oven used in this study, the on/off cycle time is 12 s. With regard to the temperature, the initial water saturation is the controlling factor on the final temperature reached. As shown in the Theory section for high-frequency heating as in the case of microwave heating, dielectric heating is the main thermal process. It has been shown by Hu and Liu[32] that, if water is

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(31) Gondiken, S. Camurlu field immiscible huff and puff pilot project. Proceedings of 5th SPE Middle East Oil Show, Manama, Bahrain, March 7−10, 1987; paper SPE 15749.

(32) Hu, K.; Liu, R. C. Theoretical study of the dielectric constant in porous sandstone saturated with hydrocarbon and water. *IEEE Trans. Geosci. Remote Sensing* **2000**, *38* (3), 1328–1336.

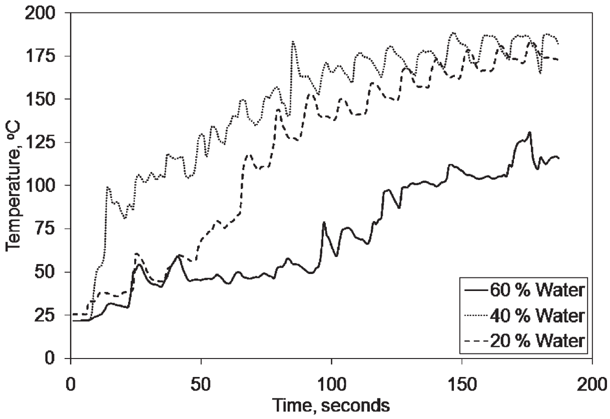

Figure 5. Temperature variations observed in mixed-wet porous media for Bati Raman crude oil with ϕ = 25.86%.

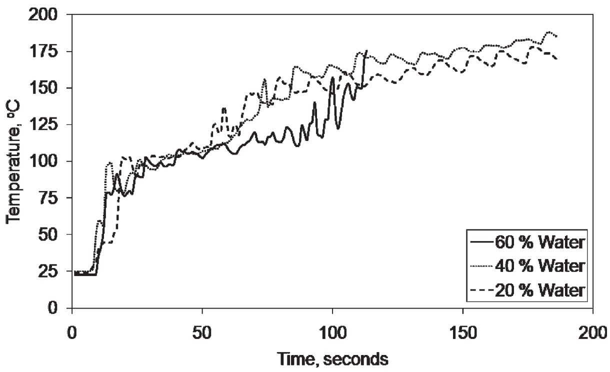

Figure 6. Temperature variations observed in oil-wet porous media for Bati Raman crude oil with ϕ = 25.86%.

continuous and oil is in a dispersed form in pore space, the effective dielectric constant approximately linearly increases with water saturation. On the other hand, if oil is continuous and water is in a dispersed phase in pore space, than a typical nonlinear relationship exists between the effective dielectric constant and water saturation. In other words, we expect a lower steady-state temperature profile in cases where the oil saturation is higher. As can be seen in Figure 4, the final temperature at the end of the experiment for the 60% water saturation case is higher compared to ones for 40 and 20% water saturation cases. Thus, the experimental and analytical results are in accordance with each other.

Effect of Wettability. Wettability is a manifestation of rock−fluid interactions associated with fluid distribution in porous media. A wetting liquid will attempt to occupy the lowest free energy positions and, hence, will preferentially flow into fine-scale porosity because of capillary forces. Figures 4−6 give temperature variations observed during experiments carried out with the Bati Raman crude at differing water saturations in water-wet, mixed-wet, and oil-wet porous medium prepared using the aforementioned aging method. It can be seen that, in all wettability cases, low water saturations lead to smaller steady-state temperature values. The steady-state temperature in the mixed-wet case was smaller than the other temperatures. It turns out that the 40% water saturation case yielded the highest temperature in all cases but the water-wet

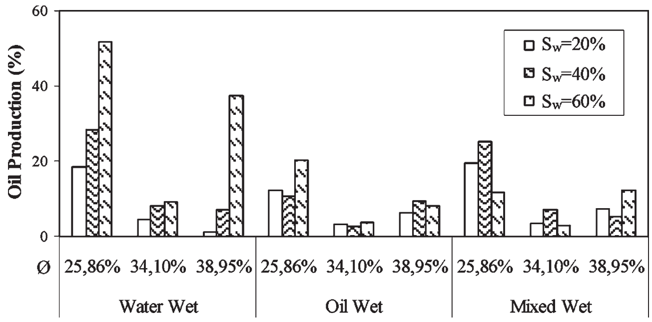

Figure 7. Cumulative oil production for different wettabilities (Bati Raman crude oil).

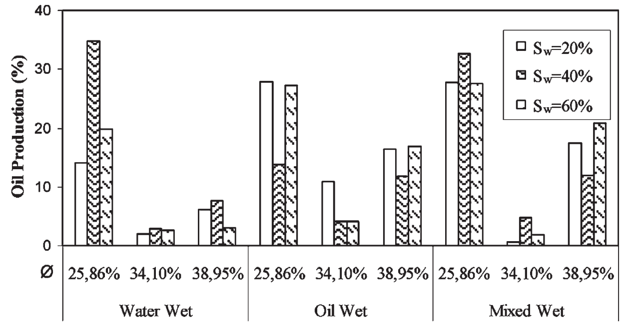

Figure 8. Cumulative oil production for different wettabilities (Camurlu crude oil).

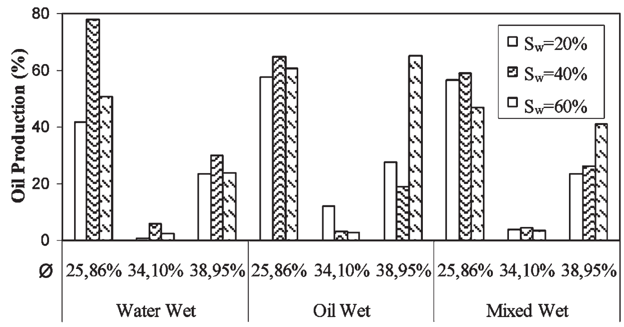

Figure 9. Cumulative oil production for different wettabilities (Garzan crude oil).

one. At low water and oil saturations, the dielectric permittivities of oil-wet media are lower than those of the water-wet ones.[33] This might be caused by the presence of an insulating oil film along the surface of the sand grains. Thus, for a water-wet medium and high water saturations, the steady-state temperature should be higher than the ones in oil- and mixed-wet cases. Because the state temperature and viscosity are inversely proportional to each other at higher temperatures, viscosity will be smaller and the process will be much more efficient. Thus, we expect a higher production if the temperature is higher. As can be seen in Figures 7−9, water- and mixed-wet productions are somewhat better than the oil-wet productions. There are cases where oil-wet porous media may lead to higher productions. These situations may be explained by small-scale heterogeneities that lead to changes in porosity and permeability of the porous medium that are believed to be due to irregular packing. However, another possibility for differing productions observed in different crudes is the effect of salinity. Salinity of the water determines the conductivity of the reservoir fluid medium and, therefore, affects the

(33) Nguyen, B. L.; Bruining, J.; Slob, E. C. Effects of wettability on dielectric properties of porous media. SPE Annual Technical Conference and Exhibition, Houston, TX, Oct 3−6, 1999.

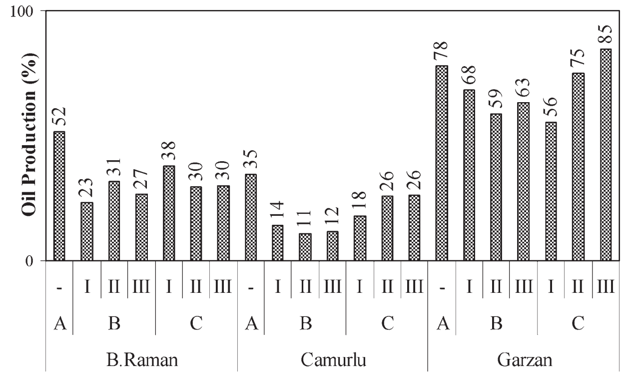

Figure 10. Periodic heating effect (A, 180 s continuous heating; B, 30 s continuous heating; C, 60 s continuous heating; I, 180 s continuous soaking; II, 240 s continuous soaking; III, 360 s continuous soaking; process is constituted in 4 cycles).

effectiveness of electromagnetic wave propagation.[34] Because the salinity of water used in Bati Raman experiments was higher than that of the Camurlu and Garzan experiments, higher salinity increases the conductance of the electromagnetic wave and may result in higher recovery. These productions compare well to previous experimental results. Chakma and Jha[34] reported recoveries as high as 45% of the original oil in place (OOIP) for oils with viscosities ranging from 1000 to 2000 mPa s.

Effect of the Heating Strategy. The optimum heating strategy was investigated by changing the heating time. To achieve this goal, three cases were considered: 30, 60, and 180 s continuous heating. Furthermore, three different soaking times (180, 240, and 360 s) were tested. It was observed that cumulative oil production was directly proportional to heating time, regardless of the oil type. As the heating time increased, the highest temperature reached at the end of a cycle increased and, thus, the production increased. While the initial production rate was not significantly affected by the operating strategy, there was an increase in the production rate at later times for runs with longer heating cycles. Thus, the overall recovery is a strong function of the temperature. In cases where longer soaking periods were applied, higher oil productions compared to continuous heating were not observed because of increased heat losses during the long soaking periods. Note that the microwave oven is not insulated. However, in real porous media, differences between continuous heating and periodic heating might be smaller because heat losses will be somewhat smaller compared to the experiments where large heat losses are present (Figure 10).

Effect of Porosity and Permeability. The effect of the porosity and, thus, permeability was considered by varying the porosity of the packing through changing the sand mesh. Note that the porosity values reported in this study are theoretical values calculated using an empirical equation. However, variations in porosity may exist because of packing. Different packing may also result in different permeabilities. That is why it is believed that, in experiments with 34.1% porosity, permeability was smaller because of packing-related heterogeneities, which lead to smaller observed production compared to the other experiments (Figure 7−9). In a typical experiment initially, the reservoir model is saturated with the reservoir fluids and, hence, the electromagnetic waves are propagated through a continuous medium without any “breaks”. As more and more oil and water are produced, voids are created, making it increasingly difficult for the weaker waves to propagate. When low- and high-porosity experiments are compared because of the presence of a small amount of oil in the pore volume, aforementioned “breaks” appear faster in low-porosity cases. High-frequency electromagnetic waves cannot easily penetrate into the partially saturated reservoir, and therefore, recovery of oil is less than comparable to high-porosity cases. Thus, as the porosity and permeability become larger, the oil rate should become larger.

(34) Chakma, A.; Jha, K. N. Heavy-oil recovery from thin pay zones by electromagnetic heating. Proceedings of the 67th Annual Technical Conference and Exhibition of the Society of Petroleum Engineers, Washington, D.C., Oct 4−7, 1992; SPE 24817.

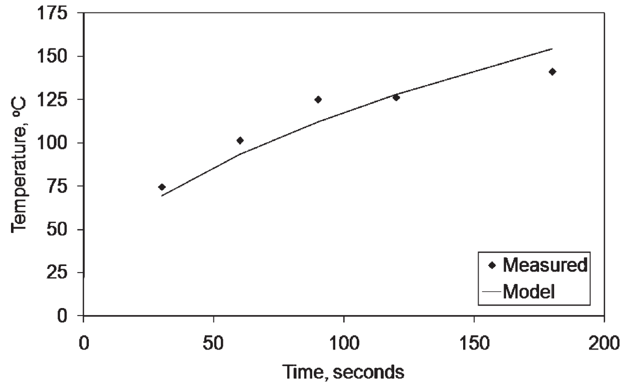

Figure 11. Comparison of the analytical model and experimental results.

Table 2. Analytical Model Results[a]

oil sample		α_e (m^{-1})/standard deviation: water wet	oil wet	mixed wet
Bati Raman	M	0.18081	0.22612	0.22289
	SD	0.085684	0.0514755	0.096222
Camurlu	M	0.21419	0.22413	0.21010
	SD	0.062746	0.0627908	0.091729
Garzan	M	0.22845	0.23015	0.20991
	SD	0.096739	0.072225	0.097138

[a] M, mean; SD, standard deviation.

Analytical Model Results. Experimental results (i.e., temperature increase as a function of time) were modeled using the aforementioned model in the Theory section by changing the electric field absorption coefficient (α_e) using a least-squares approximation method (Figure 11). This coefficient must be measured at a laboratory and is typically a function of the material that is subjected to microwave energy. It is also affected by the amount of oil and water present in the system. There are no data available stating its relationship with wettability. A sample match for an experiment carried out with Camurlu oil and 20% water is given in Figure 8. Similar matches were obtained for the other experiments carried out. Table 2 shows the electric field adsorption coefficients obtained for different wettabilities and different oils. It was observed that oil-wet conditions resulted in larger electric field adsorption coefficients compared to those obtained for mixed- and water-wet conditions. Larger standard deviations were observed for mixed-wet cases.

Conclusions

A novel graphite core holder was developed to study microwave-assisted oil production. Experimental results showed that (1) high water saturations lead to higher oil productions regardless of the viscosity of the oil, (2) high salinity water promotes microwave-assisted gravity drainage, (3) in water-wet porous media, electric large field adsorption coefficients were calculated, (4) water-wet conditions must be preferred for higher oil recoveries, (5) large porosity and permeability enhances microwave-assisted gravity drainage, and (6) continuous microwave heating gives better results compared to periodic heating because of higher temperatures reached in continuous heating.

Microwave heating is influenced by a number of parameters that can influence what is attempted. It is not like conventional heating, where the bulk sample is heated from the outside and the heat moves progressively inward; instead, the surface as well as the interior can be heated at the same time. The heating can be immediate, but under certain circumstances, there can be hot spots, while the bulk of the material is relatively cool. Understanding the possibilities can lead to unique opportunities. No definite conclusion regarding the economic feasibility of the microwave heating process for field application can be drawn at this stage. Dependent upon the different variables involved (such as wettability, viscosity of the oil, porosity, and permeability of the formation), the use of microwave power may be considered economical in one case but not in another.