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M.Sc. THESIS

"Electromagnetic Heating Methods for Heavy Oil Reservoirs"

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Abstract

The most widely used method of thermal oil recovery is by injecting steam into the reservoir. A well-designed steam injection project is very efficient in recovering oil; however its applicability is limited in many situations. Simulation studies and field experience has shown that for low injectivity reservoirs, small thickness of the oil-bearing zone, reservoir heterogeneity and other reasons limit the performance of steam injection. This paper discusses alternative methods of transferring heat to heavy oil reservoirs, based on electromagnetic energy. We present a detailed analysis of low frequency electric resistive (ohmic) heating and higher frequency electromagnetic heating (radio and microwave frequency).

We show the applicability of electromagnetic heating in two example reservoirs. The first reservoir model has thin sand zones separated by impermeable shale layers, and very viscous oil. We model preheating the reservoir with low frequency current using two horizontal electrodes, before injecting steam. The second reservoir model has very low permeability and moderately viscous oil. In this case we use a high frequency microwave antenna located near the producing well as the heat source. Simulation results presented in this paper show that in some cases, electromagnetic heating may be a good alternative to steam injection or maybe used in combination with steam to improve heavy oil production. We identify the parameters which are critical in electromagnetic heating. We also discuss past field applications of electromagnetic heating including technical challenges and limitations.

The thesis will discuss the ultra sound method in enhance oil recovery and its similar point with the high frequency electromagnetic heating method.

At last we shall point out which method of them is the most productive and economically beneficial in application. Our invention will be to use this method in transportation of oil through pipelines.

Referat

"Ağır neft yataqları üçün elektromaqnetik qızdırılma metodları"

Termik üsul ilə neft hasilatının ən geniş istifadə olunan metodlarından biri buxarın laya vurulması metodudur. Düzgün planlaşdırılmış buxarın laya vurulması layihəsi neft hasilatinda həqiqətən effektiv ola bilər. Bunula belə bir cox hallarda bu metodun tətbiqi mümkünsüz olur. Model ilə araşdırma və hasilat təcrübəsi göstərib ki, yataqların aşağı keçiriciliyi, neftli qatın qalınlığının kiçik olması, yatağın çeşidliliyi və digər səbəblər bu metod ilə neft hasilatının effektivliyini məhdudlaşdırır. Bu dissertasiya işində elektromaqnetik enerjinin alternativ metodlarından istifadə etməklə ağır neftli yataqların qızdırılmasından danışılacaq. Beləki biz kiçik tezlikli elektrik müqavimətli isitmə və yüksək tezlikli radio və mikro dalğalı elektro maqnit qızdırılma metodlarının geniş izahını təqdim edəcəyik. Biz iki model yataqda bu metodların tətbiqini göstərəcəyik. Birinci yatağın modeli keçiriciliyi olmayan gil layları ilə ayrılmış üç qum layından və özlü (qatı) neftdən ibarətdir. Bu model iki elektroddan istifadə etməklə aşağı tezlikli cərəyan ilə isidiləcək. İkinci model isə aşağı keçiricili və orta özlü neftdən ibarət yataqdır. Bu modeldə istilik mənbəyi kimi hasilat quyusunun yaxınlığında yerləşdirilmiş yüksək tezliyə malik mikrodalğalı antenadan istifadə ediləcək. Bu dissertasiya işində təqdim edlimiş nəticələr göstərir ki, elektromaqnetik qızdırma metodu laya buxar vurulmasını əvəz edən alternativ və ya neft hasilatını artırmaq üçün onunla birgə istifadə edilə bilən effektiv metod ola bilər . Burada biz elektromaqnetik istilik üçün vacib parametrləri müəyyənləşdirəcəyik. Həmçinin elektromaqnetik isitmənin real yataqlarda tətbiqləri və tətbiqi zamanı ortaya çıxan problemləri vurğulanacaq.

Tezisdə ultra səs dalğalarından istifadə etməklə neft hasilatının artirilmasınadan və onun yüksək tezlikli elektromagnit qızdırma üsulu ilə oxşar cəhəti göstəriləcək.

Sonda bu metodlardan hansının daha effektiv, məhsuldar və iqtisadi cəhətdən əlverişli olduğu vurğulanacaq. Tezisdə olan yenilik isə seçilmiş bu metodun neftin boru kəmərlərində nəqli zamanı qızdırılması üçün tətbiqi olacaq.

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Introduction

While steam injection may be an effective method for improving heavy oil production, there are certain situations where it may not work very well. These could be for:

1. Very deep formations, where heat losses in the wellbore are significant and the quality of stem reaching the formation is very low.
2. Thin pay-zones, where heat losses to adjacent (non oil-bearing) formations may be significant.
3. Low permeability formations, where the injected fluid may have difficulty penetrating deep into the reservoir.
4. Reservoir heterogeneity, where high permeability streaks or fractures may cause early injected fluid breakthrough and reduce sweep.
5. Situations where generating and injecting steam may be environmentally unacceptable (example: through permafrost) or commercially uneconomical (in space limited offshore platforms).

In this paper we discuss alternative methods for heating heavy oil reservoirs and for comparisons with ultrasound method, which may be economically viable alternatives to steam in certain situations.

The reason we present ultrasound method is that this method has got partly similar the same way of influence as high frequency heating method that is oscillating. We describe two electromagnetic heating methods low frequency electric resistive (ohmic) heating and high frequency microwave heating. We demonstrate the applicability of electromagnetic heating with two example reservoirs one which has a thin sand zones separated by impermeable shale layers and another which has moderately viscous oil and low permeability.

For tar-sands or extremely high viscosity reservoirs, where the temperature effect on viscosity is significant, electromagnetic heating could be used as a pre-heating tool to create preferential pathways for steam injection. This would minimize the heat losses during steam injection, and improve steam injection performance.

Past studies have shown some promise in the process, however there are few field applications of electromagnetic heating or comprehensive modelling efforts. Compared to other thermal IOR methods, electromagnetic heating still remains a peripheral technology, even though it the potential was recognized more than three decades ago.

Chapter II

Electromagnetic Methods for Heating Oil Reservoirs

The principle of these methods is based on electrical stimulation of the oil-bearing strata in such a manner that the oil flow is increased. Heat is supplied to the reservoir to maintain and, at the same time, increase the pressure in the oil field when its natural pressure has been reduced. The heat is supplied both as frictional heat, from the vibrations, and also as alternating current into the wells. The electrical transmission capabilities always present in an oil field allow the alternating current to flow between wells to make the reservoir function in a manner similar to an electrode furnace because of resistance heating.

The heating causes a partial evaporation of the water and the lightest fractions of the hydrocarbons and remaining gases in the oil. Furthermore, the alternating current causes the ions in the fluids to oscillate and thereby creates capillary waves on the fluid interfaces and thus reduces the surface tensions.

Electrical heating of a formation can occur in a number of ways, depending on the frequency of the electrical current. In the high frequency range (radio frequency and microwave), dielectric heating prevails, and the dipoles formed by the molecules tend to align themselves with the electric field. The alternation of this field induces a rotational movement on the dipoles, with a velocity proportional to the frequency of alternation. The molecular movement may result in significant heating, as is seen in microwave ovens. If low frequency Alternating Current is used, it is the resistive or ohmic (I^2R) heating. This method is dominant. A third method of electrical heating is inductive heating, where Alternating Current flowing through a set of conductors induces a magnetic field in the surrounding medium. The variation of the magnetic field, in turn, induces secondary currents, whose circulation in the medium generates heat.

In this paper we discuss and model low frequency electric resistive heating and high frequency microwave heating. Ultrasound method is discussed as well in order to have a better image about high frequency electromagnetic method.

Chapter III

3.1 Low Frequency Electrical Resistive Heating

Law frequency electrical heating or resistance heating is produced by passing an electric current through a resistance—obstacle which impedes current and causes it to give off heat. Resistance heating is the generation of heat by electric conductors carrying current. The degree of heating for a given current is proportional to the electrical resistance of the conductor. If the resistance is high, a large amount of heat is generated, and the material is used as a resistor rather than as a conductor. Electrical resistive heating involves the application of electrical current through the subsurface, resulting in the generation of heat. Electrical resistive heating uses the natural electrical resistance within the subsurface where energy is dissipated through ohmic, or resistive, losses. This manner of in situ heating allows energy to be focused into a specific source zone. When the subsurface temperature is increased to the boiling point of the pore water or the saturated media in the treatment zone, steam is generated. The necessary power input to the subsurface is inversely proportional to the soil resistivity and directly proportional to the square of the applied voltage, based on the following equation derived from Ohm's Law.

$$\text{Power} = (\text{Voltage})^2/\text{Resistance} \qquad (3.1)$$

The resistance of a subsurface matrix is largely determined by its water content, concentration of dissolved salts or ionic content in the water, and ion exchange capacity of the soil itself. The organic carbon content of soils also affects resistivity, but has a greater effect on the required treatment time as a result of the stronger partitioning of organic contaminants, such as chlorinated solvents, to the soils. In addition, the resistivity is a function of temperature, and as the water reaches its boiling point, the resistivity decreases with increased ion mobility.

Soil resistance can be measured in the field or estimated from characterization data for soils and groundwater. The total resistance of an electrical resistive heating system is determined based on the resistivity of the soil and the geometry of the electrode system. For matrices with a total resistance of 10 to a few hundred ohms, and applied voltages range from 100 to 1,500 volts, required power inputs will be on the order of tens or hundreds of kilowatts.

An electrical resistive heating system consists of subsurface electrodes to direct current through the subsurface. In some cases, groundwater extraction is also used to lower the water table within the treatment zone during initial stages of treatment (prior to temperatures exceeding the boiling point of subsurface water) or to provide hydraulic control. To improve the uniformity of heating and reduce local current densities at the electrodes, most configurations employ multiple phased arrays of electrodes with a central ground electrode. This method increases the available current pathways as electrodes are phased so that current can flow from one electrode to any other electrode or to the neutral ground. Larger areas are remediate by installing adjacent arrays so that the heated zones overlap.

Electrodes can be installed using several different drilling or direct-push techniques, including angled or horizontal methods. The installation method generally depends on space constraints at the surface or on the geology. Because the current density is highest at the electrodes, the applied voltage is dependent on the contact resistance. In vadose zone applications or once full steaming conditions are achieved in aquifer applications, water is typically injected to maintain good electrical contact and prevent excessive drying or voltage breakdown at the electrodes.

This injection may be augmented with low concentrations of salt added to the water and/or the use of highly conductive packing (for example, carbon/graphite or steel shot) around the electrodes. Additional equipment is required for water (or brine) injection at the electrodes.

Surface equipment varies depending on the specific method, site, and scale. Typically, utility (60 Hertz) electrical power is used with power conversion equipment to regulate voltage or to convert the phase characteristics of the power. Depending on soil properties, single arrays up to 100 feet in diameter (typical arrays are 30 to 40 feet in diameter) can be operated. Multi-phase heating requires additional space for a transformer (typically mounted on a standard tractor trailer), which can also be designed to include voltage controls.

As we mentioned, electrical resistive heating or ohmic heating may occur when low frequency alternating current flows through the reservoir, and electrical energy is converted into heat. In the simplest configuration (Figure 1), two neighbouring producing oil wells may act as cathode and anode.

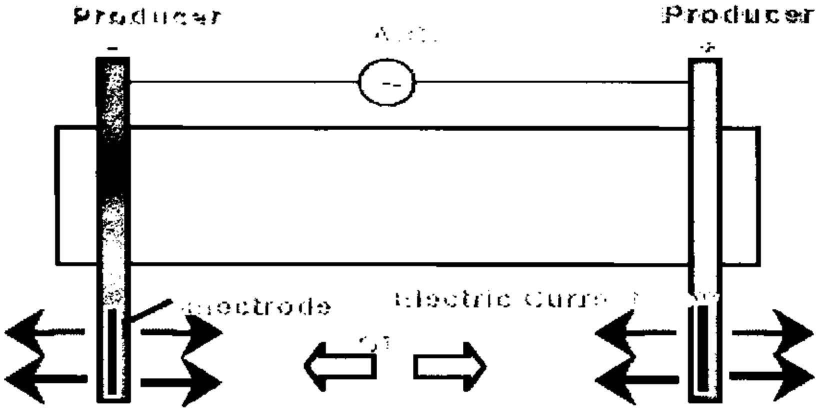


Figure 3.1. Schematic of Electric Resistive Heating

The electrical stimulation of the well can be arranged in different ways depending on the actual well configuration. The energy is delivered from a step-wise regulated transformer with a complete set of instrumentation to monitor the current, voltage and energy delivered over each phase. The power to the wellheads is delivered by cables normally buried 30 cm under the ground. The cables at the wellhead are connected to the power-carrying cable down the well, which can be:

1. By insulated casings stripped at the "pay" zone--the cables are directly connected to the casing at the wellhead.
2. By under-reaming of the existing casing above the "pay" zone--the current is delivered either by a downhole cable to the casing at the pay zone or via the tubing when using insulated centralisers.

In any of these arrangements, electrical safety is maintained by normal protection of any current-carrying parts. The wellhead itself is protected by a fence. A typical arrangement is shown in Figure 2.

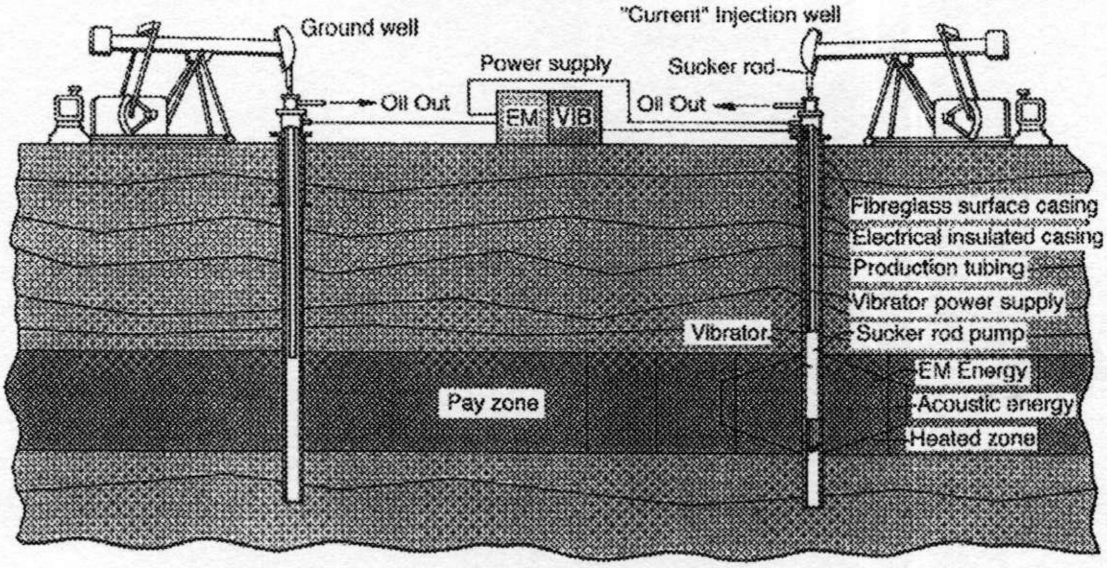


Figure 3.2. Arrangements of Resistive Heating

A potential difference is applied across the two electrodes and an electrical path through the formation is provided by the formation (in-situ) water. As such, to maintain the electrical circuit, the formation temperatures should be kept below the boiling point of water (at the formation pressure).

Conservation of electric charge requires that:

$$\overline{V}J = Q \qquad (3.2)$$

Where **J** = current density

Q = electric charge injected or extracted at a location per unit time

$\overline{V}$ = gradient operator.

It is assumed that the time derivative of the volumetric charge density is negligible since the time dependent variation of the driving electric field is slow enough for capacitive effects to be neglected.
Also, from Ohm's Law

$J = -\sigma\ \Phi$ (3.3)

Where Φ = electric potential
σ = electrical conductivity

Waxman-Smits equation (3.4) is used to capture the dependence of conductivity on temperature, saturation and lithology.

$$\sigma(T, S_w) = \phi S_w \frac{\phi S_w}{\rho_{ionic}(T)} + B(T)Q_{vb} \quad (3.4)$$

Where ρ_{ionic} = water resisitivity
B = exchange cations equivalent conductance
Q_{vb} = bulk cation exchange capacity
= $265[1-\phi]$ equiv/m^3 for sands
= $504[1- \phi]$ equiv/m3 for shales

From Equation (3.4), it is evident that presence of water is a necessary criterion for low frequency ohmic heating, as with decreasing water saturations the conductivity decreases.

As we know this paper is concerned with the recovery of petroleum fluids from an oil reservoir using electrical energy. By its very nature this problem must deal with both the equations that describe the fluid flow as well as the heat flow equations. In general, the oil in the wellbore is very viscous with the consequence that the fluid moves slowly.

As a result, the amount of oil collected in a given time is quite small. To increase the production rate of the well, the oil's velocity needs to be increased. One method of accomplishing this is by heating the fluid using an electromagnetic induction tool (EMIT). The simple principle behind the EMIT is that it heats the fluid thereby decreasing its viscosity and increasing its velocity. This method of increasing the production rate of a given wellbore is currently being utilized with the generalization that for wells of several hundred metres in length, several EMIT regions are placed in the wellbore at intervals of about one hundred metres. So that they are all supplied sufficient power, these EMIT regions are connected by a cable surrounded by a steel housing.

Investigating analytically the relationship between the temperature of the EMIT and the production rate of the oil.

One approach to this problem is to write out the full system of coupled partial differential equations that relate the temperature and the velocity flux and then to solve them numerically with an expensive computational fluid dynamics (CFD) program. Indeed, this method has been used in the past and it will be used to test the accuracy of our simplified model in the absence of experimental data. The purpose is to carefully analyse each of the physical processes in this system and by making some basic assumptions, to derive a simple set of equations that still captures the main features of the system modelled with the CFD code.

It is organised in the following way. The first it will be described the overall geometry of the problem and establishes the coordinates used to describe the model. At this point the problem is broken into three subproblems: the flow of fluid in the reservoir, the flow of fluid in the wellbore and the generation of surface temperature from the heat

sources in any EMIT regions. Parts result in a second order ODE for the oil flux for a fixed viscosity. The third part is found that the temperature of the fluid is inversely proportional to the velocity. Fluid that moves slowly past an EMIT region will absorb more heat than the same amount of fluid that moves quickly past an EMIT. As a result, slowing the fluid velocity increases the temperature and therefore decreases the viscosity. This viscosity is used in parts a. and b. thereby closing the system of equations. It is described relationship between the axial changes in the fluid flux and the pressure in the wellbore is derived. The details of where a relationship for the velocity and the pressure from the Navier-Stokes equations is obtained by averaging over the radius of the wellbore. Under the assumptions made, the pressure is found to be related to the radius of the wellbore by a form of Poiseuille's law.
Finally, last details the derivation of the temperature equations. This derivation is complicated by the fact that there are four radial regions of the radial problem to consider; EMIT, casing, reservoir and wellbore with the first three forming the boundary conditions for the heat equation in the wellbore region. Furthermore, there are three axial regions: EMIT region, cable region, and a region where there is neither EMIT nor cable. The results together illustrate the analytical solution of the resulting model in the simple situation when no heat is applied to the oil.

We discuss numerical results of the simplified model with respect to the results predicted by the CFD code. On comparison, we find considerable qualitative agreement between the two models which is quite remarkable considering their relative complexities.

Figure 3.3 depicts the overall geometry of the problem. A horizontal cylindrical well extends from $z = 0$ to $z = L$. Fluid flows radially into the well from the surrounding media and is drawn out with a pump which is located at z = L where a fixed pressure of PP is maintained.

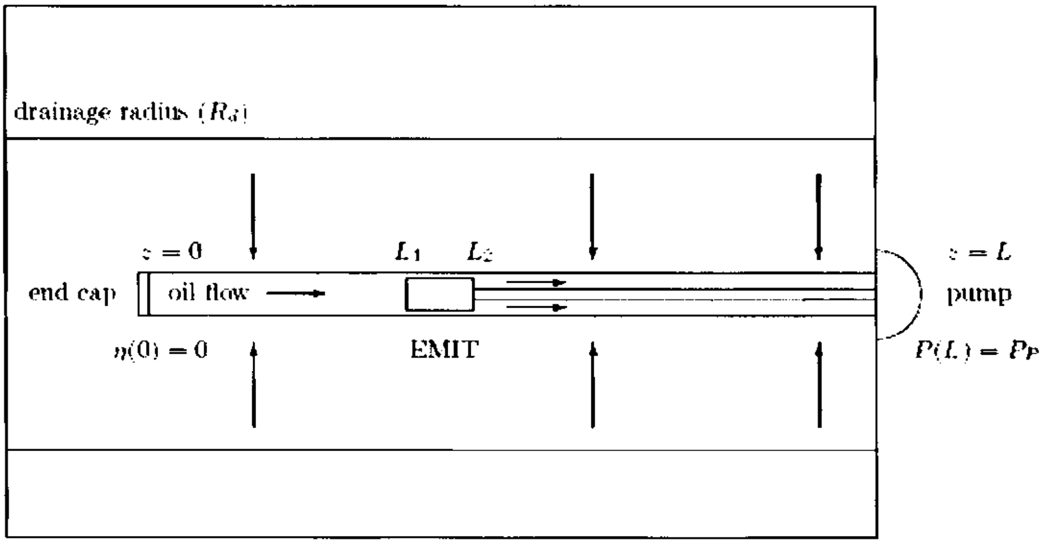


Figure 3.3. Overall geometry for the horizontal wellbore

At z = 0, where the end cap is situated, the motion of the flow is radially inward (no horizontal flow at this point). As one increases in z, the action of the pump comes into effect and imparts a horizontal component to the fluid flow.

This figure shows only one EMIT region which extends from z = L_1 to z = L_2. It is in these EMIT regions that the oil is heated. Power is supplied to the EMITs through a cable housing resulting in three different regions. Starting at the pump we have a cable housing region that extends to the first EMIT. If there are other EMIT regions then they must also be joined with cable housing and evenually, after the last EMIT region, the wellbore is open with no impediment to the horizontal flow.

Once the horizontal well is drilled, fluid seeps from the surrounding region into the wellbore. Once inside the wellbore, the fluid is drawn out with a pump that maintains a fixed pressure at one end of the well. The rateat which the fluid seeps into the wellbore is a function of the pressure differential and the viscosity of the fluid.

Indeed, the flow rate (volume/time) of the fluid into a segment of the wellbore of length Δz is given by the expression [3.5]

$$q(z) = \frac{2\pi k[P_R - P(z)]}{\mu_o \ln(R_d/R_c)} \Delta z \qquad (3.5)$$

where k is the permeability of the reservoir, P_R is the reservoir pressure, P (z) is the pressure inside the wellbore at the axial position z, μ_o is the viscosity at the ambient temperature T_a , R_d is the drainage radius and R_c is the outer radius of the casing.

Since we are assuming that we are at a steady state, we make the assumption that the radially flowing fluid remains unheated until it reaches the inner radius of the casing at which point it instantly becomes heated to the temperature of the fluid at that particular z position. Consequently the viscosity in the expression will remain as μ_o even once the temperature of the wellbore is increased.

Using equation one can find an expression for the average axial velocity of the fluid, $\bar{v}$ (z). Let R_z denote the inner radius of the wellbore which could be zero, the radius of the EMIT tool, R_e, or the outer radius of the electrical housing, R_h . Using this definition of Rz, let η(z) = $\pi(R^2 - R^2)$ $\bar{v}$ (z) which is the flux in the wellbore. The advantage of using η(z) rather than $\bar{v}$ (z) is that η(z) is a continuous function whereas the velocity $\bar{v}$ (z) is not.

Figure 3.4 shows an infinitesimal annular section of the wellbore of length Δz. At z = $z_{□}$ the axial flux is η($z_{□}$) while the radial flux is given by the expression. By the conservation of mass, these two components combine to give the axial flux at $z = z_{□} + \Delta z$.

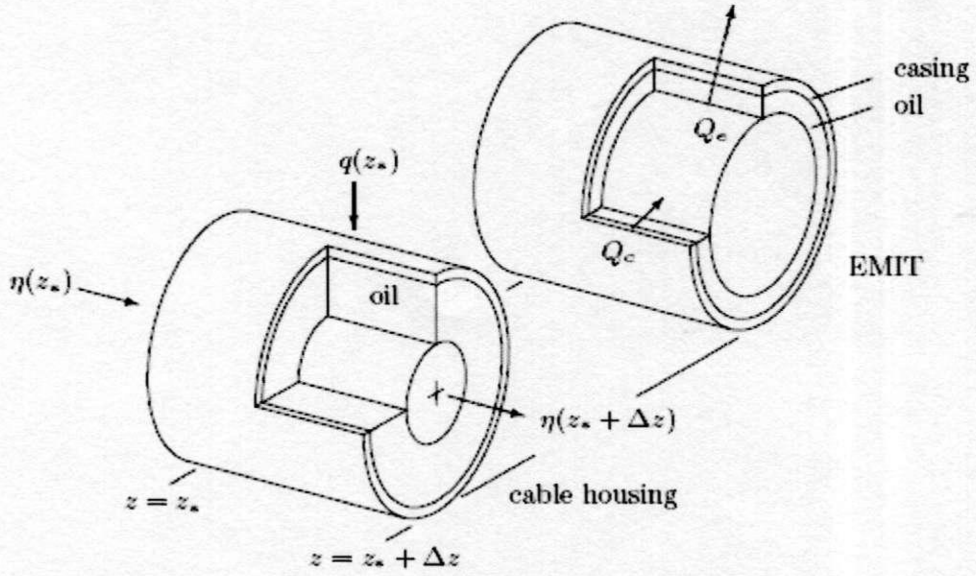


Figure 3.4. An Infinitesimal of the wellborefor the EMIT

In other words,

$$\eta(z_*) + \frac{2\pi k[P_R - P(z_*)]}{\mu_o \ln(R_d/R_c)}\Delta z = \eta(z_* + \Delta z). \tag{3.6}$$

Rearranging terms and letting $\Delta z \to 0$ gives the expression

$$\frac{d\eta}{dz} = \frac{2\pi k[P_R - P(z)]}{\mu_o \ln(R_d/R_c)}; \qquad \eta(0) = 0. \tag{3.7}$$

The boundary condition $\eta(0) = 0$ just expresses our approximation that the axial fluid velocity is zero at the end of the wellbore. Since $P(z) < P_R$ throughout the wellbore, $d\eta/dz > 0$ which is consistent with having the fluid flux increase as it approaches the pump located at $z = L$.

A relationship between wellbore pressure and flow velocity is obtained from the Navier-Stokes equations for an incompressible viscous fluid,

$$\rho\frac{\partial\vec{v}}{\partial t}+\rho(\vec{v}\cdot\nabla)\vec{v}=-\nabla P+\mu\Delta\vec{v}. \qquad (3.8)$$

Again refer to figure 4 where we consider an arbitrary yet constant cross section. Assume a steady fluid flow inside the wellbore that propagates in the $\hat{k}$ direction. Assuming that the flow is radially symmetric, we have $\vec{v} = v(r)\hat{k}$ and the continuity equation is automatically satisfied.

For the purposes of this discussion, we assume that the wellbore has a steady state temperature distribution that is a function of r and z alone. As well, to simplify the expressions, we will take the far field temperature to be zero. We also assume that thermal conduction in the z direction is negligible. The primary sources of heat are the EMIT regions and the casings around them and it is assumed that the heat production is uniform. Since the reservoir and casings are porous, heat is connected radially in them. In the wellbore, oil flows along the axis and therefore heat is convected axially in the wellbore.

Consider the casing. In this region, the total rate of heat flow is the sum of the flow due to heat conduction and the flow due to the movement of fluid in the radial direction. The result of this is that the heat flux in the casing is given by

$$\vec{\Phi}_c=\left(\lambda_c\frac{\partial u}{\partial r}+\rho C_f v_r u\right)\hat{\mathbf{r}}. \qquad (3.9)$$

We have denoted the temperature as u(r; z), the radial speed of the fluid as v_r, the conductivity of the casing as λ_c and ρC_f for the fluid heat capacity.

For any closed region the total heat energy produced must equal the total heat energy lost. Let Qc be the amount of heat energy produced in the casing per volume per unit time.

When we apply heat to wellbore, it is this fluid in the wellbore that is heated and not the fluid in the surrounding region.

3.2 Features of the Simulation Model

1. The simulation model is a Cartesian, three-dimensional model with 24 x 24 x 18 grid blocks of $\Delta x = \Delta y = 14.32$ ft and Δz is variable, with finer gridding near the horizontal wells (and electrodes).
2. The middle sand is 30 feet thick, whereas the top and bottom sands are 10 feet in thickness. The three sands are separated by two impermeable shale layers of 5 feet thickness. Its schematic is shown in Figure 3.5.

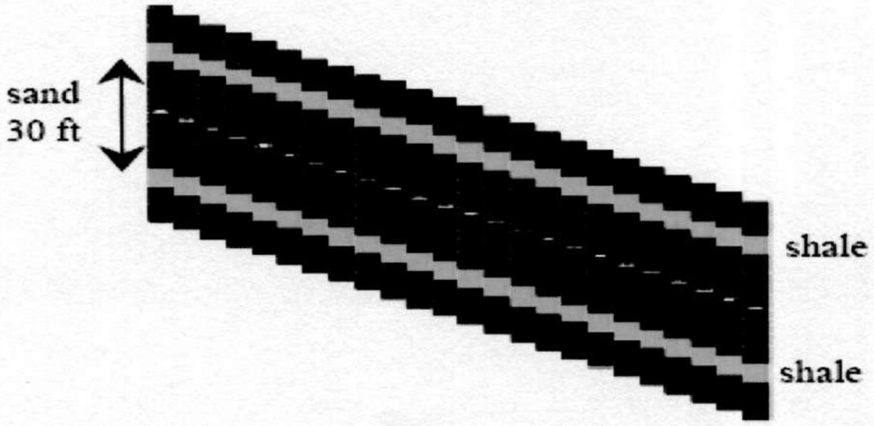


Figure 3.5. Cross-Section Schematic of Reservoir Modeled for Low Frequency Electric Heating (Example 1).

3. Heavy oil has been represented as a single-component oil of 14.1° API and molecular weight of 400.
4. Heavy oil viscosity at the initial temperature of 95°F is 9541 c p. Viscosity temperature relationship is given in Table 1.

Table 1. Oil Viscosity-Temperature for Example 1.

Temperature (F)	Oil viscosity (c p)
95	9541.0
100	6543.0
120	2230.1
140	866.4
160	410.9
180	213.4
200	122.4
210	90.0
220	74.8
240	47.3
280	23.0
340	9.6
380	7.0
400	5.2
500	3.0
600	1.4
800	1.0
1000	0.5

5. The sands in the reservoir model have $k_x = k_y = 2{,}500$ md, $k_z/k_x = 0.5$, $\phi = 0.36$, Initial reservoir temperature = 95°F, initial oil saturation = 0.5, initial water saturation =0.5. The shales have water saturation = 1.0. Initial reservoir pressure = 360 psia at the formation top depth of 800 ft. The reservoir has a 10 degree dip.
6. Two horizontal electrodes are placed at X=1 and X=24, in the middle sand (Z=9). It is assumed that the horizontal wells serve as the electrodes. The preheating runs were performed at 300V, 2-phase AC at 60Hz.
7. Constant steam injection rate of 200 Bbls/Day of CWE at Steam Quality = 0.7 is maintained throughout the simulation period. Coordinates of the injector are X=13, Y=16.
8. Producers operate under a constant flowing bottomhole pressure constraint of 14.7 psia.
9. Injector is completed in layers 4 through 9 (bottom three layers) whereas the horizontal producers in Layer 9 (X=1 and X=24) are completed throughout.

10. Relative permeability curves are specified using power-law type relations with S_{wc}=0.45, S_{org}=0.12, S_{orw}=0.23, S_{gc}=0.0, k_{rocw}=0.8, k_{rwro}=0.12, k_{rgro}=0.45, N_w=N_{og}=N_{ow}=N_g=2.

3.3 Analysis of Electric Resistive (Ohmic) Heating Simulations

It was simulated low frequency electric resistive heating for a period of 6 months. At the end of 6 months the temperature distribution in layer 9 (containing the horizontal electrodes) is shown in Figure 3.6.

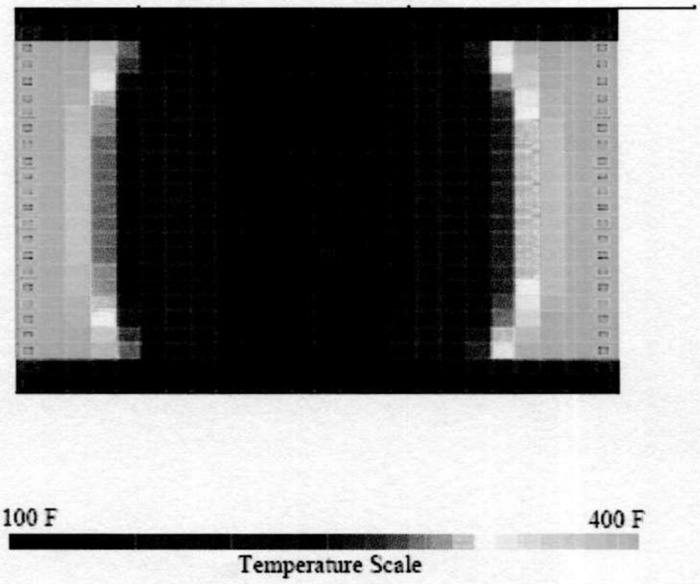


Figure 3.6. Temperature at 6 months of preheating (in layer 9).

Ohmic Heating is a near well-bore effect, with temperatures reaching 400°F near the two electrodes. At a distance of 60 feet from the well, the temperature after 6 month of pre-heating is about 170°F (or 75°F over the initial reservoir temperature of 95°F, see Figure 3.7).

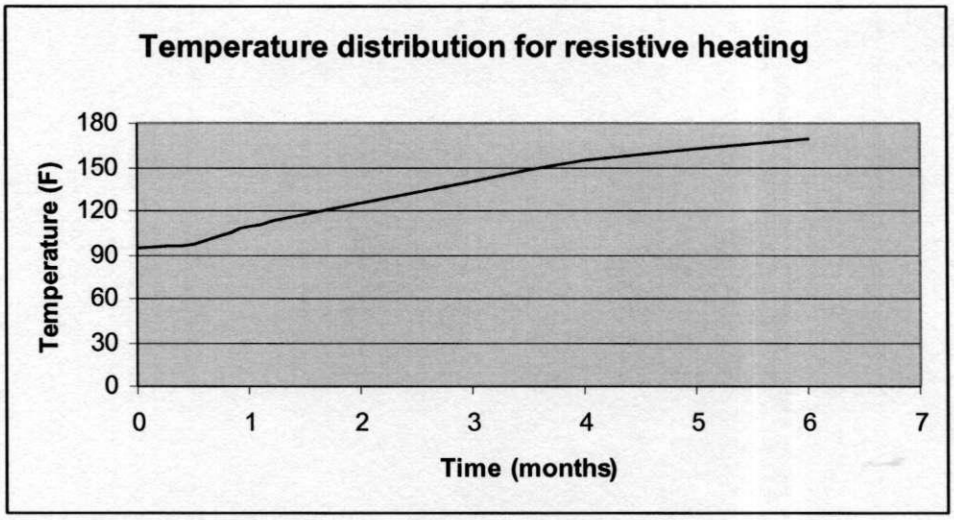


Figure 3.7. Temperature at 6 months of resistive heating

After 6 months of preheating, steam is injected from the central injector, located at X=13, Y=16. The temperature distribution after 2 months and 1 year of steam injection following electric pre-heating is shown in Figures 3.8 and 3.9 respectively.

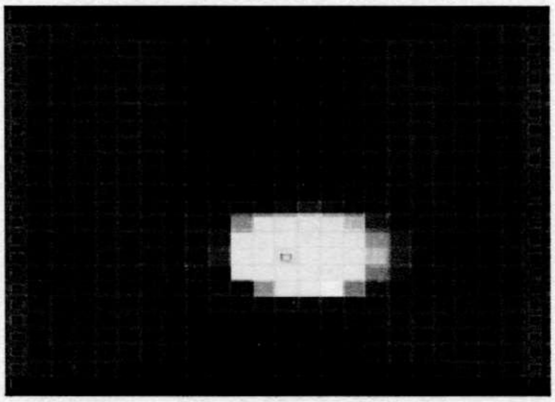


Figure 3.8. Temperature after 2 months of Steam Injection after 6 months of pre-heating (in layer 9)

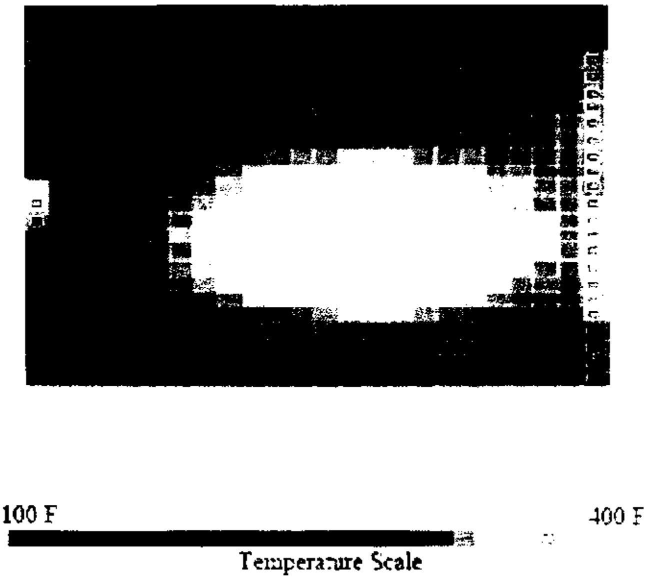


Figure 3.9. Temperature after 1 year of Steam Injection after 6 months of preheating (in layer 9)

It is evident from the simulation results that electric pre-heating allows for a more-uniform and widespread heating of the reservoir. This translates into accelerated production at the beginning and higher cumulative oil during the duration of the simulation. The length of the electrodes, power requirements and time for preheating can be optimized for specific projects. We do not present any optimizations in this paper.

An important consideration in Ohmic Heating simulations is to appropriately handle the effect of water saturation on heating. As the temperature rises in the reservoir, and boiling occurs, the resistivity increases (following Waxman and Smits model presented in Equation 3.4). This reduces the current and heating decreases (as it is proportional to I^2).

Keeping the temperature below the boiling point of water at reservoir pressure helps distribution of electric heat in the broader.

The presence of shales, having Sw=1.0, also has a significant effect on heating. Figure 3.10 shows the temperature distribution across the X-Z cross-section of the simulation model when shale is present. In comparison to Figure 3.11 (when shale is absent), the heated zone in Figure 3.10, is stretched out or elongated.

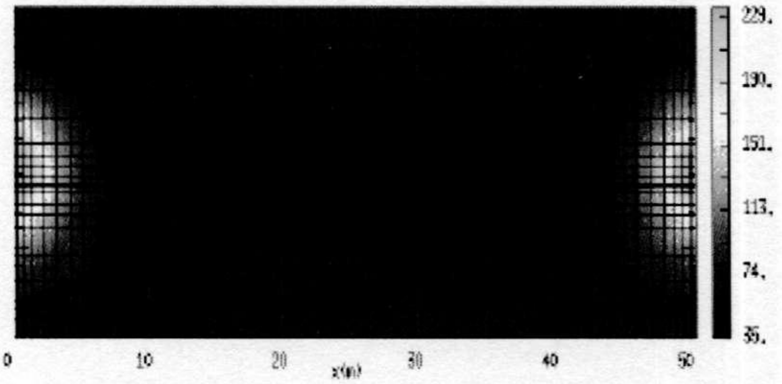


Figure 3.10. X-Z cross-section of Example 1 showing temperature distribution after 12 months of electric heating.

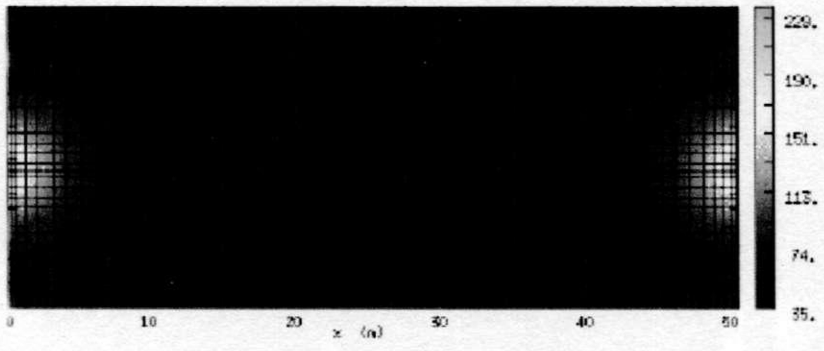


Figure 3.11. X-Z cross-section of Example 1 (without the shales) showing temperature distribution after 12 months of electric heating.

This happens because the higher conducting shale conducts current further into the reservoir, increasing the heated region. The location of the electrodes with reference to the water-bearing shale can be optimized for best over-all heating.

Chapter IV

4.1 High Frequency Electromagnetic Heating

High frequency generates heat by dielectric hysteresis (loss) within the body of a nominally non-conducting material. The heating of a nominally electrical insulating material is due to its own electrical (dielectric) losses, when the material is placed in a varying electrostatic field. The resultant heat is generated within the material, and in homogeneous materials is uniform throughout. High frequency electromagnet heating is a rapid method of heating and is not limited by the relatively slow rate of heat diffusion present in conventional heating by external surface contact orby radiant heating.

Its principal mechanism is dipole rotation by which non-conductive material can be warned in an electromagnet field. Dipole rotation - molecular rotation occurs in materials containing polar molecules having an electrical dipole moment, which will align themselves in the field by rotating in place; as the field alternates the molecules reverse direction, and the successive rotations causes heat through friction at the molecular level. Dipole rotation is the mechanism normally referred to as dielectric heating.

From Maxwell's equations the following simplified expression for average power dissipated in a volume V can be derived:

$P_{ave} = \omega\varepsilon_o\varepsilon'' E^2 V$ watts (4.1)

or

$\overline{p} = \sigma E^2$ watts per cubic meter

Where

conductivity $\sigma = \omega\varepsilon_o\varepsilon''$ (4.2)

and

ω = radian frequency
ε_o = free space dielectric constant
ε'' = loss factor (proportional to the electromagnetic energy absorbed by the porous media)
E = rms electric field intensity in volts per meter.

As electromagnetic energy is absorbed by the porous media, the increase in temperature can be calculated from the following simple equation:

$$\sigma E^2 dt = \rho c_p dT \quad (4.3)$$

where

ρ = mass density in kg/m^3
c_p = specific heat at constant pressure

$$\frac{dT}{dt} = \frac{\sigma E^2}{\rho c_p} \quad (4.4)$$

For an imposed electric field E, the rate of temperature increase depends on $\frac{\sigma}{\rho c_p}$.

The dielectric constant varies with frequency and temperature, and can be measured in the laboratory.

Dielectric heating is the phenomenon in which radio-wave or microwave electromagnetic radiation heats a dielectric material, especially as caused by dipole rotation.

4.2 Microwave Heating

The penetration depth of microwaves is usually small, but for relatively mobile reservoir fluids the microwave energy continuously heats fluids as they are drawn towards the producing well. The microwave antenna can be placed in a drilled hole close to the producing well. A schematic of the microwave heating process is shown in Figure 4.1.

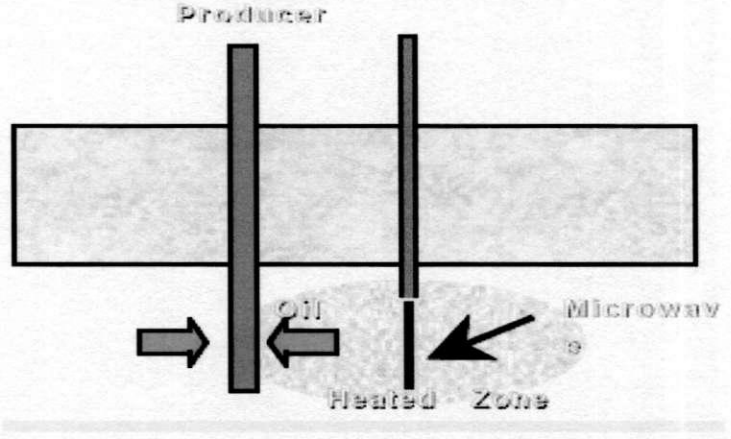


Figure 4.1. Schematic of Microwave Heating

The microwave energy distribution may be obtained from an analytical solution to the antenna equation. The solution presented here represents the solution for a single point source, and the complete antenna consists of a linear array of these point sources. The energy absorbed by the grid block i (per unit volume per unit of time) due to the k'th point k source, P_i^k is calculated according to the coordinates of the i grid block and its relation to the source.

For a block i containing a point source,

$$P_i^k = \frac{2P_o^k\alpha^2}{V}\left[\frac{1}{(2\alpha^2)} - \left(r^2 + \frac{r}{\alpha} + \frac{1}{2\alpha^2}\right)e^{-2\alpha r}\right] \qquad (4.5)$$

where

α = attenuation of block i

r = equivalent radius for block i (radius of a sphere having the same volume as block i)

P_i^k = energy absorbed by block I due to the k`th point source (which is block i)

P_0^k = antenna power for k`th point source in the linear array

V = volume of block i

A 3-D, 3 Phase (oil, water and gas) finite difference simulator TERASIM was used to study the process of microwave heating. A 17*17*34 grid block model was created to simulate a 2.5 acre region, which is about 900 feet in thickness. The reservoir permeability and initial oil saturation through a cross section in the middle are shown in Figure 4.2.

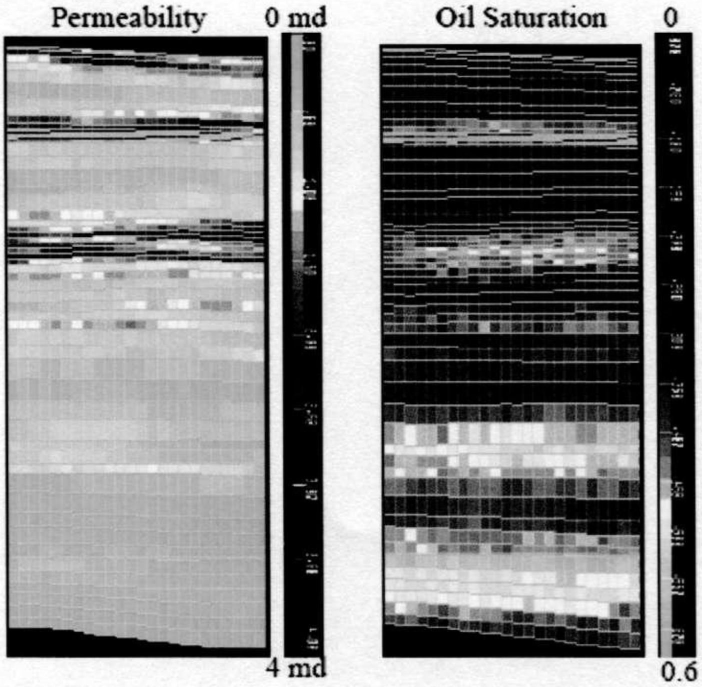
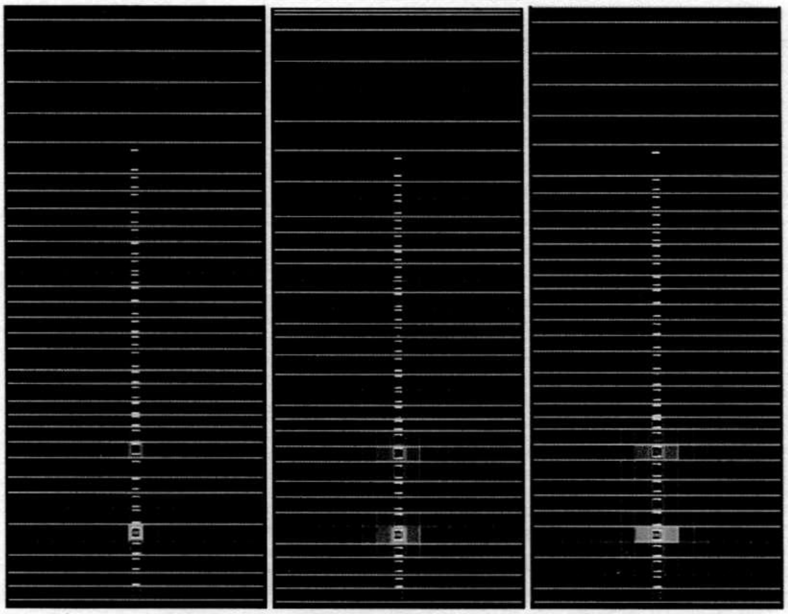


Figure 4.2. Permeability and Oil Saturation for Example 2.

We set the microwave antenna (frequency = 0.915 GHz) in the lower part of the formation (Figure 4.3) at a distance of about 30 feet from the producing well. Heating the lower layers of the formation has a distinctive advantage because of a combination of factors; higher pressures, the reservoir model has better initial oil saturation in the lower layers (as seen in Figure 4.2) and that gravity drainage aids in improving recovery.



Time = 1Year

Time 5 Years

Time = 10 Years

Figure 4.3. Temperature distribution for case 6: 60 kW microwave source in Layer 30 and another 60 kW microwave source in Layer 25.

4.3 Features of Simulation Model

1. The simulation model is a Cartesian, three-dimensional model with 17 x 17 x 34 grid blocks of Δx=19.41 ft, Δy=22.85 ft. The producer is fractured and fracture half-width = 400 ft. Δz is variable, and the layers containing the microwave source have Δz = 30 ft.

2. Oil viscosity at the initial temperature of 95°F is 33.11 c p. Viscosity Temperature Relationship is shown in Table 2.

Temperature (F)	**Oil Viscosity (c p)**
95	33.11
111	15.86
150	6.031
200	2.057
250	1.002
300	0.607
350	0.427
400	0.330
450	0.270
500	0.235
550	0.209
600	0.193

Table 2. Oil Viscosity-Temperature for Example 2.

3. The model represents a heterogeneous layered reservoir with very low permeability. Figure 4.1 shows a cross-section of the permeability field

through the centre of the model. $\phi = 0.47$. Initial oil saturation is given in Figure 4.4.

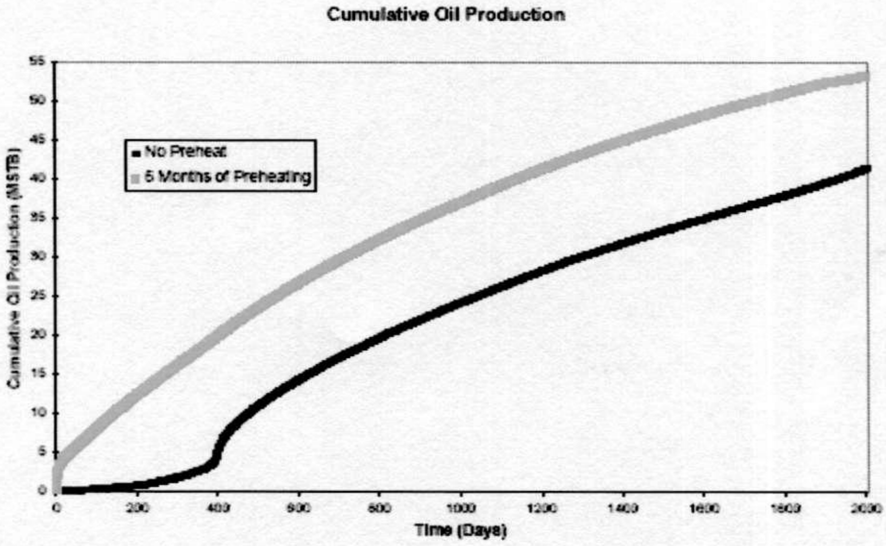


Figure 4.4. Cumulative Oil Production from Horizontal Wells with and without Preheating

4. Initial reservoir pressure for simulation = 194 psia at the formation top depth of 806 ft. In the lower layers where the microwave antenna is located, the initial pressure is around 1300 psia.
5. The microwave antenna is assumed to be 30 ft in length and placed at a distance of 30 ft from the producing well.
6. The frequency of the microwave source is 0.915 GHz.

The power and number of sources was varied the results presented in this paper are for:

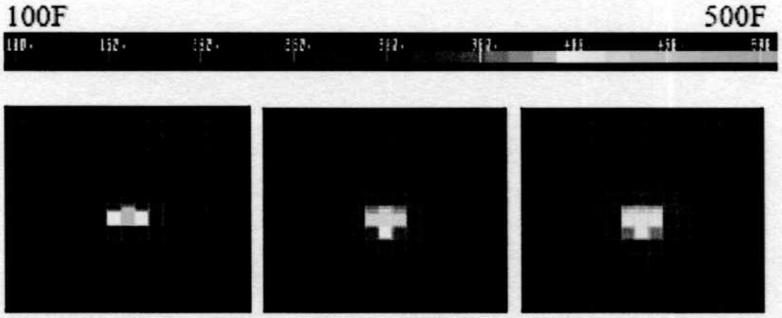
a) Case: 1 30 kW source in Layer 30
b) Case: 2 45 kW source in Layer 30
c) Case: 3 60 kW source in Layer 30

d) Case: 6 60 kW source in Layer 30 and a second 60 kW source in Layer 25.

7. Producer operates under a constant flowing bottomhole pressure constraint of 90 psia.

4.4 Analysis of Microwave Heating Simulations

Simulations conducted using the TERASIM microwave simulator show that temperature at a distance of 60 feet from the microwave source increases to around 400°F (or 305°F over the initial reservoir temperature of 95° F). Temperature maps are shown in Figures 4.3 and 4.5, whereas Figure 4.6 plots the radial distribution of temperature from a 60 kW microwave source.



Time = 1Year Time 5 Years Time = 10 Years

Figure 4.5. Temperature distribution for case 6 (Layer 30.).

Figure 4.7 compares the cumulative oil production for microwave heating scenarios with primary production. When two 60 kW sources are placed (Case 6) in Layers 25 and 30 respectively, there is an 80% improvement in cumulative oil recovered over primary production in 10 years. The power requirements after 10 years of heating were estimated to be around 200-250 kW-hr/Incremental Bbl of Oil produced for the various cases discussed.

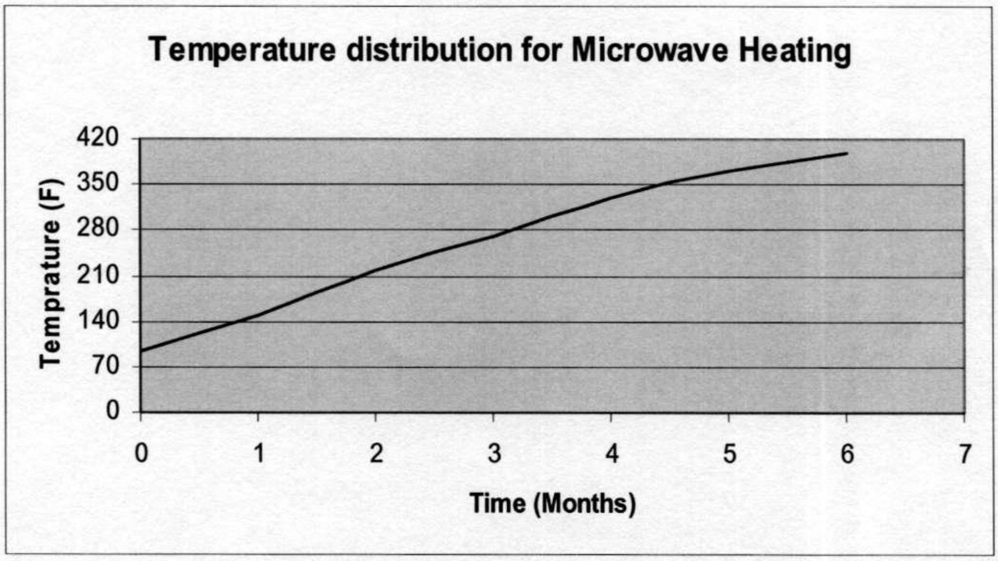


Figure 4.6. Temperature distribution around Microwave Source (case 6)

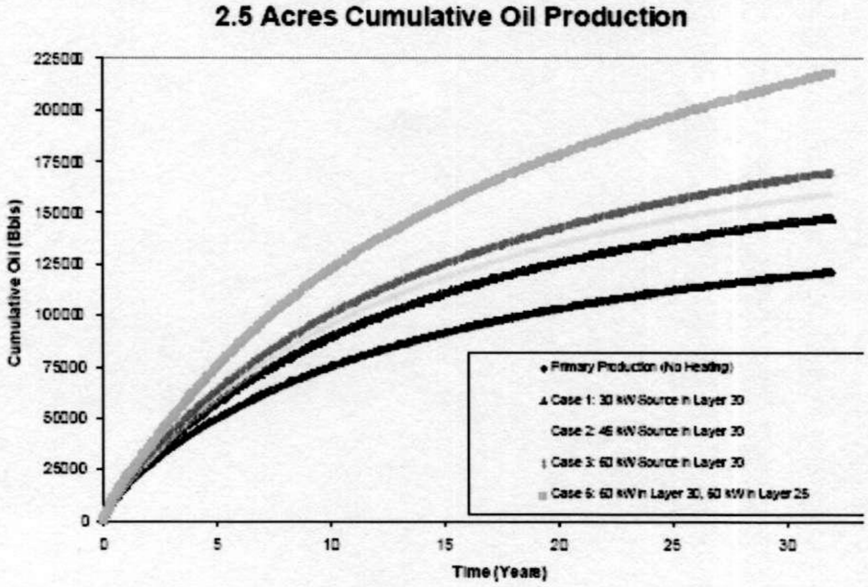


Figure 4.7. Cumulative Oil Production for Various Scenarios for Example 2.

A Base Case with primary production is also provided

Chapter V

Ultrasound Method

A well known problem associated with oil and gas production is the general reduction over time in the amount that can be extracted from a field. Typically, the natural pressure in a subterranean oil field is sufficient to result in no more than about ten percent of the oil contained in the formation. The residual amount is difficult to produce because of its very low mobility. Accordingly, recovery of these residual amounts is of great concern to the oil and gas industry.

Elastic waves have been observed to increase productivity of oil wells, although the reason for the vibratory mobilization of the residual organic fluids has not remained unclear. Residual oil is entrapped as ganglia in pore constrictions because of resisting capillary forces. An external pressure gradient exceeding an "unplugging" threshold is needed to carry the ganglia through. The vibrations help overcome this resistance by adding an oscillatory inertial forcing to the external gradient; when the vibratory forcing acts along the gradient and the threshold is exceeded, instant "unplugging" occurs. The mobilization effect is proportional to the amplitude and inversely proportional to the frequency of vibrations. We observe this dependence in a laboratory experiment, in which residual saturation is created in a glass micromodel, and mobilization of the dyed organic ganglia is monitored using digital photography. We also directly demonstrate the release of an entrapped ganglion by vibrations in a computational fluid-dynamics simulation.

To better understand the reason why the elastic waves can mobilize residual organic fluids, one should recall why these fluids are trapped. The primary reason for the entrapment is capillary forces, which arise from differences in the diameters of pore channels through which the organic fluids are driven by external pressure gradients. It has been suggested therefore that the mechanism of vibratory mobilization of the ganglia entrapped in pore constrictions should be sought in the effects of vibrations on capillary forces.

The oil and gas industry has painstakingly attempted to develop efficient and effective methods for enhanced oil recovery (EOR). Historically, the prior art is replete with methodologies designed to augment oil and gas production, including water, steam and gas injection, chemical surfactants, hydraulic and explosive fracturing, and layer burning. Recent scientific observations of earthquake activity, however, show a correlation between seismic waves generated by the earthquake and nearby oil and gas production.

Scientific experimentation to duplicate the effects of seismic waves produced by an earthquake has been successful in stimulating the production of oil and gas fields. There are promising new technologies being developed which produce elastic wave energy for well stimulation. The effect of elastic wave energy has been proven to alter the permeability of subterranean oil formations, which has an excitation effect and can appreciably increase the mobility of the oil.

An elastic wave energy approach to well stimulation avoids the well known disadvantages associated with the historically known methods, which were largely undesirable because they were costly, required shutting in production, and created harmful ecological consequences.

New technologies being developed for elastic wave stimulation of oil are currently focused on ultrasonic wave generation and on vibroseis-type wave generation. However, there is a need for an improved approach to generating elastic wave energy, preferably one that employs well known drilling methodologies to provide an inexpensive yet effective and reliable approach. Furthermore, there is a need for an improved approach that is capable of stimulating more than one well at once in order to reduce the expense and complexity of the procedure.

In the recovery of oil from oil-bearing reservoirs, it is usually possible to recover only minor portions of the original oil in place by the so-called primary recovery methods which utilize only the natural forces present in the reservoir. A variety of supplemental recovery techniques have been employed in order to increase the recovery of oil from subterranean reservoirs.

The principle is based on sonic stimulation of the oil-bearing strata in such a manner that the oil flow is increased.

This is done by introducing special vibrations into the strata. These vibrations will be as identical to the natural frequency of the rock matrix and the fluids as possible.

The vibrations give rise to several effects in the fluids and remaining gases in the strata. They decrease the cohesive and adhesive bonding, as well as a substantial part of the capillary forces, thereby allowing the hydrocarbons to flow more easily in the formation.

The vibrations that propagate into the reservoir as elastic waves will change the contact angle between the rock formation and the fluids, thereby reducing the hydraulic coefficient of friction. This allows a freer flow towards the wells where the velocity increases and creates a greater pressure drop around the well. The elastic waves give rise to an oscillating force in the strata, which results in different accelerations because of the different densities in the fluids. The fluids will "rub" against each other because of the different accelerations to create frictional heat, which in turn reduces the surface tension on the fluids.

The vibrations also release trapped gas that contributes to a substantial gas lift of the oil. Furthermore, the oscillating force creates an oscillating sound pressure that contributes to the oil flow.

The most widely used supplemental recovery technique is waterflooding which involves the injection of water into the reservoir. As the water moves through the reservoir, it acts to displace oil therein to a production system composed of one or more wells through which the oil is recovered.

It has long been recognized that factors such as the interfacial tension between the injected water and the reservoir oil, the relative mobilities of the reservoir oil and injected-water, and the wettability characteristics of the rock surfaces within the reservoir are factors which influence the amount of oil recovered by waterflooding. It has been proposed to add surfactants to the floodwater in order to lower the oil/water interfacial tension and/or alter the wettability characteristics of the reservoir rock. Processes which involve the injection of aqueous surfactant solutions are commonly referred to as surfactant waterflooding or as low-tension waterflooding, the latter term having reference to the mechanism involving the reduction of the oil-water interfacial tension. Also, it has been proposed to add viscosifiers such as polymeric thickening agents to all or part of the injected water in order to increase the viscosity thereof, thus decreasing the mobility ratio between the injected water and oil and improving the sweep efficiency of the waterflood.

An object of the present chapter is to improve operations involving the use of ultrasound technique to improve oil recovery. There is provided a method for recovering oil from a subterranean formation including injecting an aqueous composition into said formation and displacing said oil toward one or more production wells; subjecting the aqueous composition to an ultrasonic signal to release oil from the formation; and removing the aqueous composition containing oil from said one or more production wells.

As shown in the figure 5.1, an ultrasonic source 115 is suspended by cable 110 within the borehole 105 of the waterflood injection well 200 to release oil porous rock layers 130.

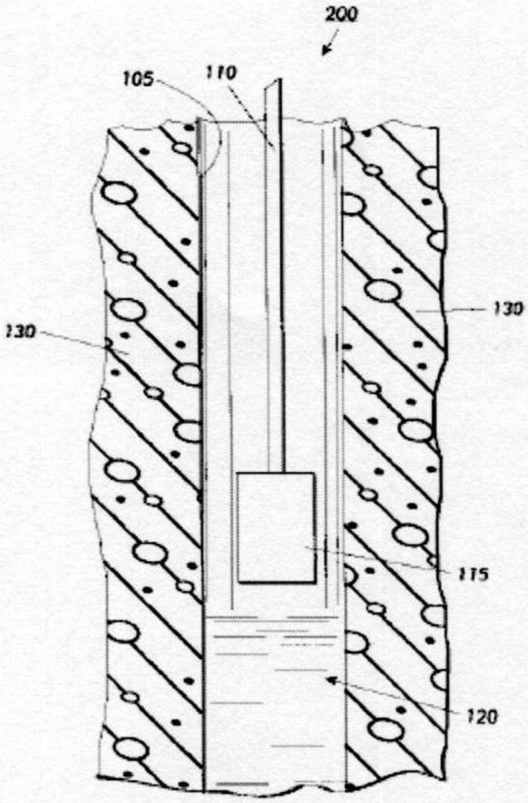


Figure 5.1. Schematic of an apparatus

The areas of the oil reservoir through which injected water or other injected fluids flow is referred to as being on the percolation path for fluid transport. Adjacent areas are referred to as being off the percolation path. Ultrasonic source 115 employs an acoustic slow wave technique is to obtain motion of fluids not on the percolation path of motion achieved via static or quasi-static fluid pressure gradients. Enhanced oil recovery by forcing heated water or steam through the rocks is secondary recovery. The fluid flooding by heated water or steam opens percolation flow through the porous rocks along a limited number of paths. Use of ultrasound techniques with frequencies tailored to oil densities and viscosities and rock pore sizes or particle sizes can excite acoustic slow waves in the trapped oil. These slow wave excitations will induce an oscillatory motion in the pore fluids; both in situ water, oil, and injected fluids. These oscillatory motions move these fluids, including oil, from one pore to adjacent pores. If there is no percolation flow in the neighborhood, the oscillatory motions cancel on alternate ultrasonic wave half cycles and no net oil motion results. If, however, there is neighboring percolation flow then it acts to break the back and forth oil motion symmetry by removing oil on the ultrasound cycles that push oil onto the percolation flow path. Thus the ultrasound induces continual oil migration to percolation paths, where it can be recovered by the fluid flow along these percolation paths. This constitutes a method of tertiary recovery not currently utilized. This would be accomplished by superposing the acoustic slow wave frequency ultrasonic oscillation on the pressure pulse of the water or steam forced into the rocks. The issues discussed below for feedback techniques for controlling the oscillation frequency also apply here.

Ultrasound frequencies could be superposed on the fluid flows used in tertiary oil recovery in several ways. One approach is to add an ultrasonic transducer either within the water pump output pipe, or surrounding the water pump output pipe. Another approach is to suspend an ultrasonic probe within the pipe at the appropriate depth level where oil is to be recovered in the ground.

Having in mind the main elements of the present invention, and not wanting to be limited to theory, the present invention is believed to operate as follows: when a rock containing a pore fluid, be it in situ water, oil, or injected fluid, is subject to a sound wave, the fluid and the rock will oscillate in the direction of propagation of the sound wave. In general, the fluid and the porous rock respond at slightly different rates. In the limit of very low frequency the porous rock and the pore fluid will respond completely in phase, resulting in no net motion of the pore fluid with respect to the surrounding rock. As the frequency of the driving sound wave increases, the viscous fluid motion lags slightly behind that of the approximately rigid solid. This results in fluid motion through pores in the rock. As the frequency increases, the phase lag in relative motion between the rock and liquid also increases, at least up to a point. At a point called the acoustic slow wave point the motion of the solid and liquid will be 180 degrees out of phase. At this point we have the maximum amount of motion of the pore fluid with respect to the porous rock. See figure 5.2 for an illustration of the oil motion near a waterflood percolation flow path under the influence of an acoustic slow wave.

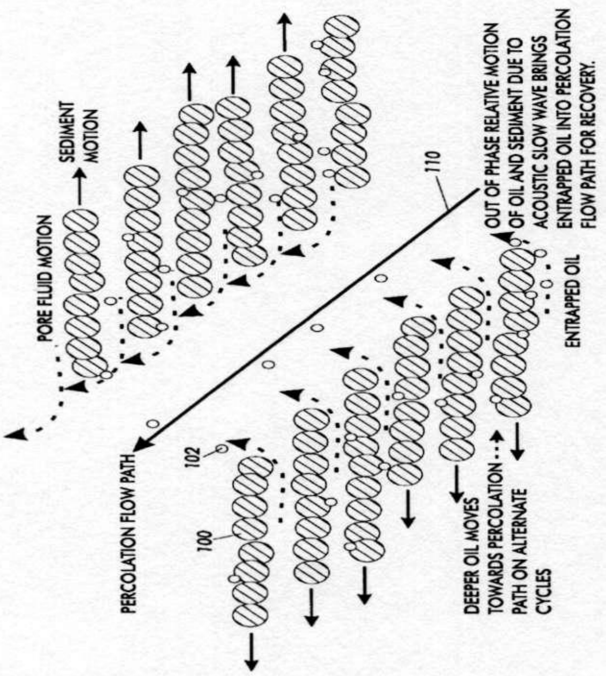


Figure 5.2. Motions of Oil or Pore Liquids

Thus, when excited at the slow wave frequency, on alternate sound wave half cycles the maximum amount possible of pore fluid is moved from previously inaccessible pores adjacent to the percolation flow path into the flow path, where in can be carried away. On intervening sound wave half cycles fluid containing surfactants from the percolation flow path is injected into surrounding pores in the rock, thus increasing the size of the percolation flow domain. Thus, both ultrasound half cycles perform useful functions for secondary oil recovery: removing previously inaccessible oil from rock surrounding the percolation flow path, and enlarging the area of the oil reservoir accessible to surfactants and percolation flow.

The first analysis of these different modes of fluid motion was carried out by Biot and has been a topic of continuing research. The acoustic slow wave mode is also sometimes called the "compressional slow wave" or just the "slow wave". These waves have been observed experimentally in a variety of porous solids, and are well verified.

The frequency of the acoustic slow wave mode, f_c, in an infinite porous solid is given by

$$f_c = \eta\phi/(2\pi k\rho_f) \qquad (5.1)$$

where

η is the fluid viscosity,

ϕ is the aggregate porosity,

k is the reservoir permeability,

ρ_f is the fluid density.

The rock porosity ϕ depends on the volume fraction of solids in the reservoir via:

$$\phi=1-(\% S/100) \qquad (5.2)$$

where

%S is the percent of solids in the rock, by volume.

The rock porosity ϕ can be estimated from sonic logs using the Wyllie relationship, from density logs, from neutron logs, or from resistivity logs via Archie's formula. In addition, porosity can be obtained directly from rock core samples removed from the area of the oil reservoir during drilling operations. The analysis of such well log and core data is well known to those skilled in the art.

Similarly, the reservoir permeability can be estimated from well logs by techniques well known to those skilled in the art. In addition, reservoir permeability can be estimated directly from waterflooding pressure-water flow curves from a particular reservoir.

Thus, the magnitude of required acoustic slow wave frequencies can be predicted directly from Equation 1 by using well log and other geophysical data, such as in situ oil density and viscosity, commonly available for a given oil reservoir.

To illustrate that required slow wave frequencies are in physically accessible domains with ultrasonic equipment commercially available, we calculate acoustic slow wave frequencies for several different sediment size ranges. In this analysis we make use of the Carmen-Kozeny equation, as discussed in Williams. This approximation has the advantage of being a physically plausible form suggested by physical arguments, with a phenomenologically determined prefactor:

$$k = B\phi^3 / S_v^{\,2}(1-\phi)^2 \qquad (5.3)$$

where B is a constant, and S_v is the particle surface area per unit volume within the aggregate. S_v will depend on the particle size and packing of the particles, and is inversely proportional to particle diameter. Several specific particle packings have been used to calculate both S_v (for use in Equations (5.1)-(5.3)) and %S using information on the packings provided in Williams. For example, for cubic close packing of particles, the porosity ϕ=0.476, and $S_v = \pi$/D, where D is the particle diameter. For body centered cubic packing the porosity ϕ=0.395, and $S_v = 2\pi$/D. For face centered cubic packing the porosity ϕ=0.26, and $S_v = 4\pi$./D. For random packing the porosity ϕ=0.63, and $S_v = \pi$/D. Thus, the parameter S_v is related to sediment size. This information on S_v, plus Equations (5.2)-(5.3) allow the compressional slow wave frequency to be estimated by Equation (5.1). This information on S_v, plus Equations (5.2)-(5.3) allows the compressional slow wave frequency to be estimated by Equation (5.1). This information on S_v, plus Equations (5.1) and (5.3) allow the compressional slow wave frequency to be estimated by:

$$f_c = \eta\{S_v^{\,2}(1-\phi)^2\}/(2\eta B\phi^2\rho_f) \qquad (5.4)$$

Useful compressional slow wave frequency can be in the range between ±15% of the calculated or measured peak slow wave frequency.

Using these results, it is possible to estimate the slow wave frequency as a function of percent solids, %S, (or equivalently, rock porosity (ϕ=100-%S) and its dependence on sediment size. Actually, since in most reservoirs the particles have undergone metamorphosis that has resulted in grains being glued together, or in some cases such as carbonates separate grains never existed, it is better to think of these "particle" sizes rather as typical pore sizes.

It is, therefore, evident that there has been provided a method for improving oil recovery using ultrasound technique, in accordance with the present invention, that fully satisfies the aims and advantages hereinbefore set forth. While this invention has been described in conjunction with one embodiment thereof, it is evident that many alternatives, modifications and variations will be apparent to those skilled in the art. Accordingly, it is intended to embrace all such alternatives, modifications and variations as they fall within the spirit and broad scope of the appended claims.

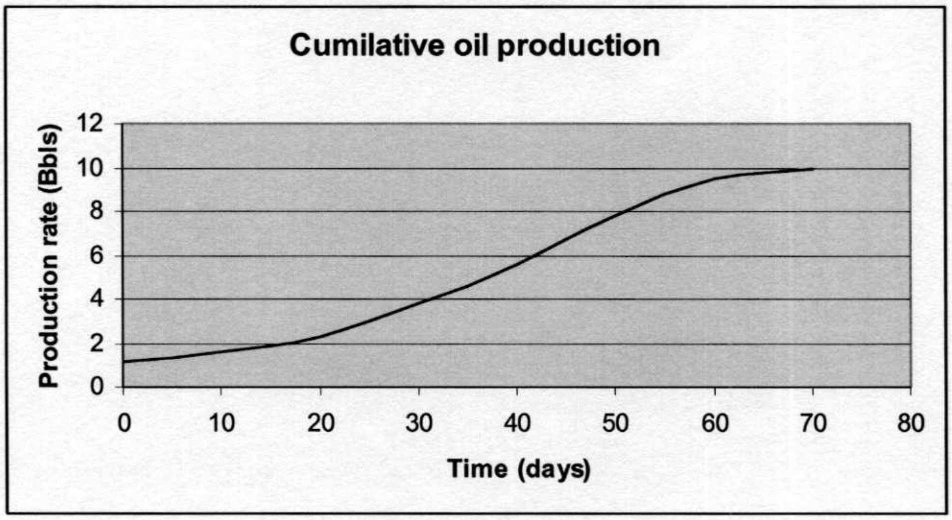
The chief difference between the elastic-wave mobilization of residual oil and the other enhanced-recovery methods is in the means of delivering the mobilizing energy. The traditional methods, which utilize hydraulic paths to supply additional forcing to the trapped ganglia, suffer from bypassing effects, in which the agents flow with water along preferential paths of least resistance, leaving hydro logically isolated oil pools untapped. In contrast, seismic energy has no preferential path and reaches every point of the porous space.

The percentage of mobilized oil will grow with larger amplitudes and lower frequencies.

Chapter VI

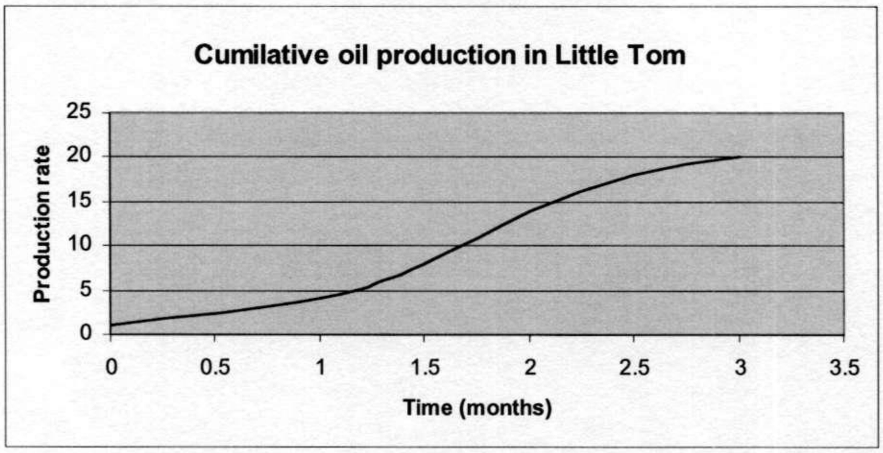
Some Field Applications

Pizarro and Trevisan presented data from a low frequency electrical heating field test at the Rio Panan field in Brazil. Production increased from 1.2 Bbls/day to 10 Bbls/day after 70 days of applying an average power of 30kW across neighbouring producing wells (328 feet apart) in a reservoir with rather viscous oil (2500 cp at reservoir conditions).



Production rate after the application of electrical heating at the Rio Panan field in Brazil

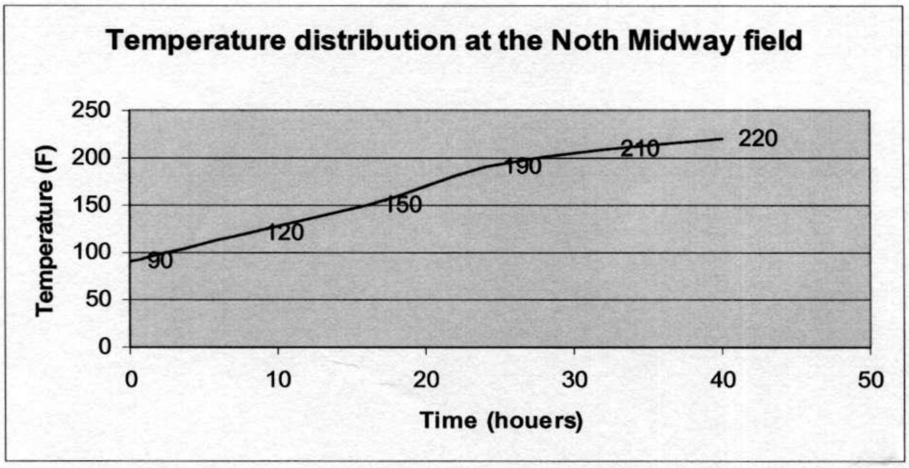
The electrical heating of a reservoir formation was used to enhance oil production as early as 1969, when an experiment in Little Tom, Tex., was successful. The production of four wells had increased from 1 bbl/d (0.16 m.sup.3 /d) to an impressive average of 20 bbl/d (3.18 m.sup.3 /d) for the experiment. The method subsequently attracted the attention of an increasing number of investigators and engineers, and their field tests were reported within a few years.



Production rate after the application of electrical heating at the Little Tom in Texas

Kasevich et al. performed a laboratory study of RF heating, in which low permeability diatomite samples filled in a 55 gallon drum were heated with an electric monopole. After 49 minutes of heating with a 400 watts and 50.55 MHz source, the temperature rose by 125C.

Subsequently a field test was carried out at the North Midway field. The test well was located where the diatomite interval was relatively homogeneous, starting at 500 feet. A mobile RF heating system was assembled around a 25 kW, 13.56 MHz generator. The RF applicator was 25 lengths and placed at a depth of 620 feet, enclosed in a 250 feet RF transparent glass/epoxy composite liner. Borehole temperature measured at 605 feet depth, rose to approximately 220°F (approximately 130°F above formation temperature of 90°F) after 40 hours of RF heating.



Temperature distribution after 40 hours application of RF heating at North Midway field

Radio frequency field tests carried out in the oil shale of Utah13 showed a good heating potential. A RF power source a 40 kW radio transmitter was used at a frequency of 13.56 MHz. The RF power levels were kept in the range of 5 kW to 20 kW and temperatures were recorded in the range of 340°C - 400°C. Two radio frequency field tests in tar sands of Utah13 were carried out in 1981. RF power input to the tar sand test volume varied between 40 and 75 kW and average temperatures of about 120°C-200°C were achieved for the two experiments.

Davison presented field test results of electromagnetic stimulation of Llyodminster Heavy Oil Reservoir (~11.4 API). Though production response to electrical heating was observed, casing insulation failure led to early termination of the test.

Chapter VI

Summary and Conclusions

It was modeled pre-heating a reservoir with thin sands separated by shale layers with two horizontal electrodes, operating at 300V and 60 Hz (2 Phase AC). Low frequency Ohmic Heating is a near well-bore effect, with temperatures increasing by 300°F near the two electrodes for the example reservoir. The temperature and pressure increase occur not only in the vicinity of the well, but also between the wells, depending on the paths of the electrical potential between the well. At a distance of 100 feet from the well, the temperature increase after 6 month of pre-heating is about 75°F. Following steam injection after pre-heating provides a uniform distribution of heat in the reservoir.

Simulations show that electrical pre-heating significantly accelerated early production and resulted in better cumulative oil production compared to the non pre-heated case for the duration of the simulations.

It was also performed simulations which show that high frequency microwave heating may be used for stimulating oil production in moderately viscous, low permeability reservoirs.

The microwave source could be located in a well close to the producer (~ 30 feet) and operate at a frequency close to 1 GHz. Simulations show that a 60 kW microwave source could increase formation temperatures by 300°F near the source within a year of heating. This results in an 80% increase in cumulative oil production over primary production when two 60 kW microwave sources are placed in the formation over a period of 10 years.

The different variations of electromagnetic heating: microwave frequency, radio frequency and ohmic heating, may be applied, depending on reservoir and fluid properties.

The energy input for each well depends on the oil flow and the set temperature in the bottom zone. This means that for a particular electrode (casing) temperature, which depends on the equipment, the power input depends on the cooling effect of the oil produced. The greater the oil production, the greater the energy input possible because the increased heat at the well area is drained away by the oil produced. If no oil is produced, the heat flow into the formation from the well would take place by heat conduction only.

Electrical conductivity increases with increasing water saturation, and for oil sands may be proportional to approximately the square of the saturation. Low frequency (~ 60 Hz) electric resistive heating could be achieved by applying a potential difference across two electrodes attached to two producing wells in the formation. The electric circuit is completed through the formation, with the in-situ water providing the conductivity. However, electric resistive or ohmic heating is reduced where there is little water content or if the water is heated above its boiling point to form steam. In such cases, higher frequency electromagnetic waves can propagate for much larger distances, and heat regions relatively far from the electrode. A region devoid of water near a severely overheated electrode, presents a very large resistance at 50-60 Hz while it is easily permits propagation of a high frequency electromagnetic wave.

Another major consideration in Electromagnetic Heating is wellbore power transmission and associated power losses. In addition to heating the formation, the electric current produces heat in the wellbore delivery system. To improve the efficiency of Electromagnetic Heating, it is necessary to keep the power dissipated in the wellbore delivery system to a small fraction of the power dissipated in the formation. It is the disadvantage of the resistive heating method.

Stroemich et al. have shown that for many common well-bore casings, current levels as low as 100 A rms cause non-linear magnetization of the well-bore steel. This in turn causes hysterics power losses in the casing and leads to impedances that are much greater than those observed at low current levels. A good understanding of the electrical properties of insulating materials and their degradation under temperature, pressure and fluids must be known so that current leakage through the electrical insulation may be assessed and maximum allowable well-bore and electrode temperatures may be set. Such precautions would help in minimizing the risks of electromagnetic heating field tests.

Hence, we can understand that the second method is much more effective then resistive heating method, because of the following disadvantages of the resistive method: Power losses due to casing and rock heating; the power dissipated in low frequency electromagnetic method is spent not only for heating liquids in formation but also for heating rock and casing as well. But in high frequency electromagnetic heating method only liquid is heated. Because high frequency waves does not heat crystal (solid) items as friction of their molecules is not possible in this event.

My invention in electromagnetic heating method is to use this high frequency electromagnetic heating method in transportation of crude oil through pipeline. Well designed high frequency electromagnetic heating system could be installed around the pipeline. Running (flowing) oil through the pipeline will be heated by the high frequency waves. These waves heat only the fluid in the pipeline, but not the pipeline itself. That is why there is no power loss because of no-pipe (iron) heating. Reduction of power loss will reduce our expenses in power.

Furthermore as temperature of oil increases, viscosity of oil decreases. Thus, it gets easier to pump oil through the pipeline. Because of low viscosity of oil, it needs less pressure to pump crude oil through the pipeline from one destination to another destination. Therefore, economic efficiency of oil transportation increases by **power saving** in heating process and **decrease of required pressure for oil pumping** process, using less pressure.

In order to better understand importance and efficiency of this method in oil transportation BTC pipeline could be mentioned as an example.

The start of BTC pipeline is at the Sangachal terminal near to Baku that receives all the oil from ACG offshore oilfields. The temperature at the receiving terminal will be 30° C, allowing the oil flow freely, although it will gradually lose heat. In the mountains, especially in the winter, ambient temperatures of -40° C and ground temperatures of -5° C are likely to result in an increase in viscosity. Besides, the oil has a high wax content of 8% to 14% by volume that in low temperature will easily deposit. Deposited wax inside the pipeline will narrow the pipe and consequently impede the flow of the oil. To use such kind of heating equipment could be a good solution to both these problems: the viscosity of oil could decrease and deposition of wax could be prevented, thus we could keep oil in such condition that we could freely transport oil without having any obstacle (deposited wax) in the pipeline and using less power for pumping process. Hence we could increase economic efficiency of oil transportation by decreasing transportation fee with low pressure pumping.

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