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(54) **METHOD FOR ENHANCED OIL RECOVERY
USING CYCLIC STEAM STIMULATION AND
ELECTROMAGNETIC HEATING**

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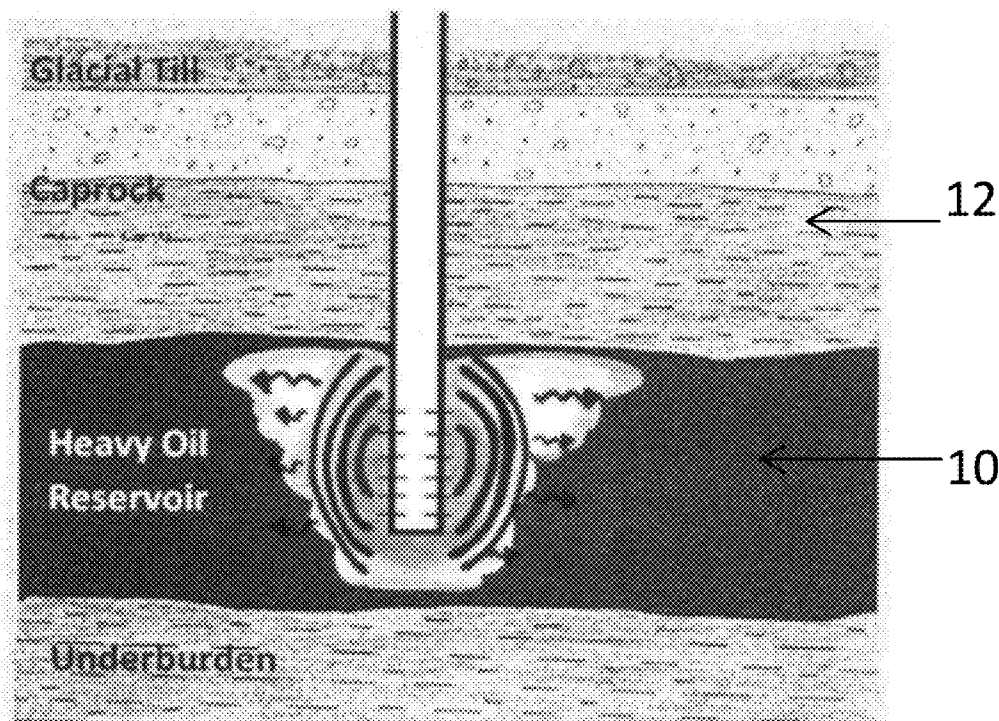
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(57) **ABSTRACT**

A method for enhanced oil recovery using cyclic steam stimulation (CSS) and electromagnetic heating (EMH). One or more CSS cycles are conducted on a subsurface hydrocarbon reservoir in order to dilate the reservoir and improve permeability, followed by EMH application for thermal recovery of the hydrocarbon to surface. The alternating process can be repeated as desired while economically viable. The method is particularly applicable to produce heavy hydrocarbons such as bitumen or heavy oil from a heterogeneous reservoir that has low permeability.



PHASE “3”

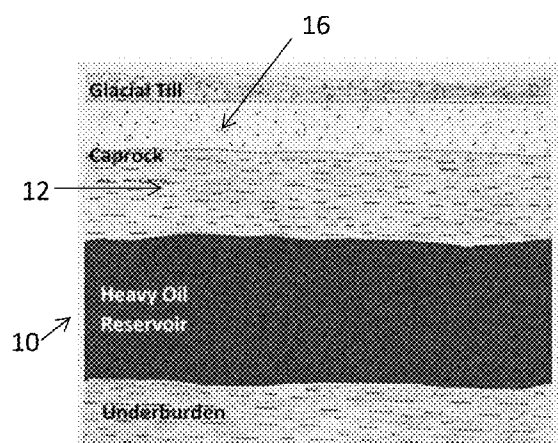


FIG. 1A
PHASE "0"

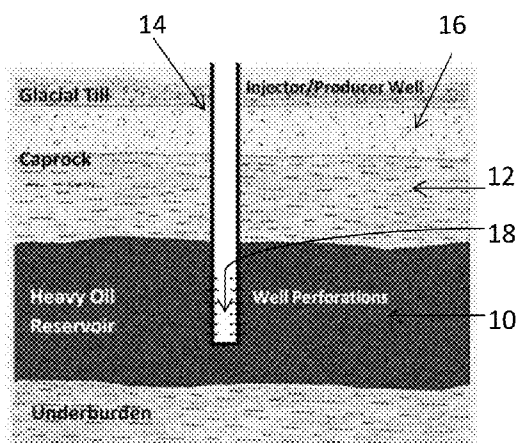


FIG. 1B
PHASE "1"

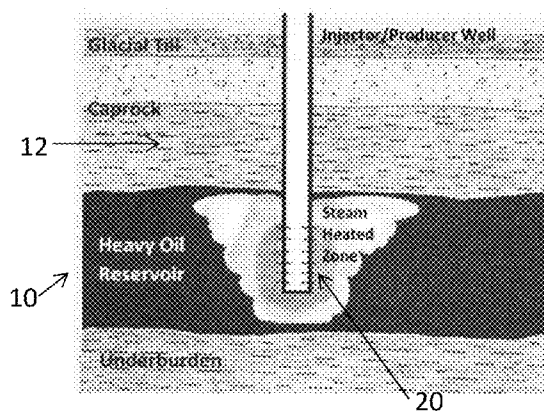


FIG. 1C
PHASE "2"

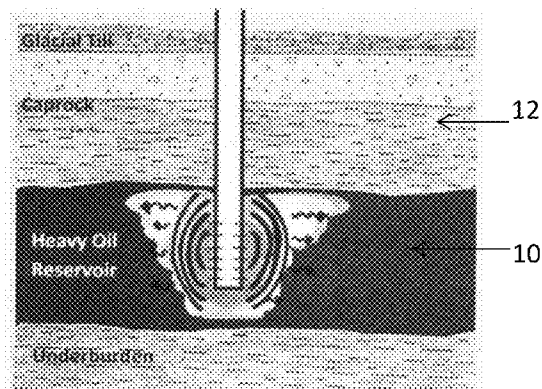


FIG. 1D
PHASE "3"

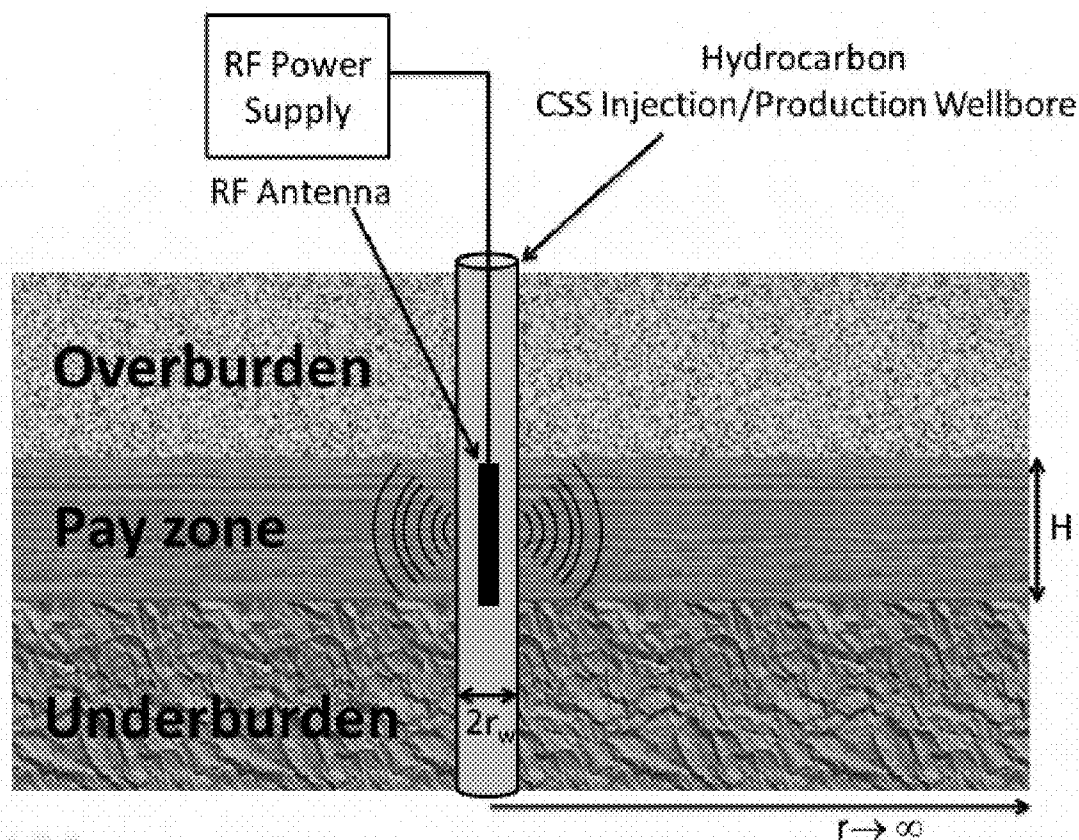


FIG. 2

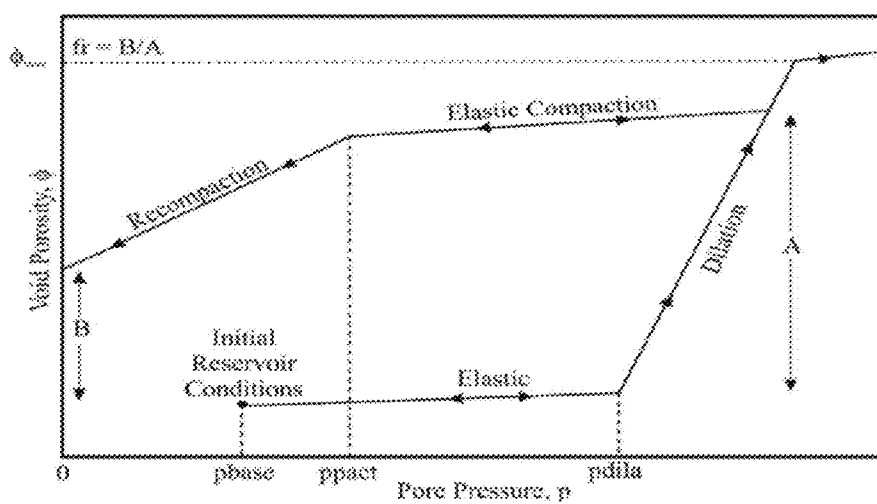


FIG. 3

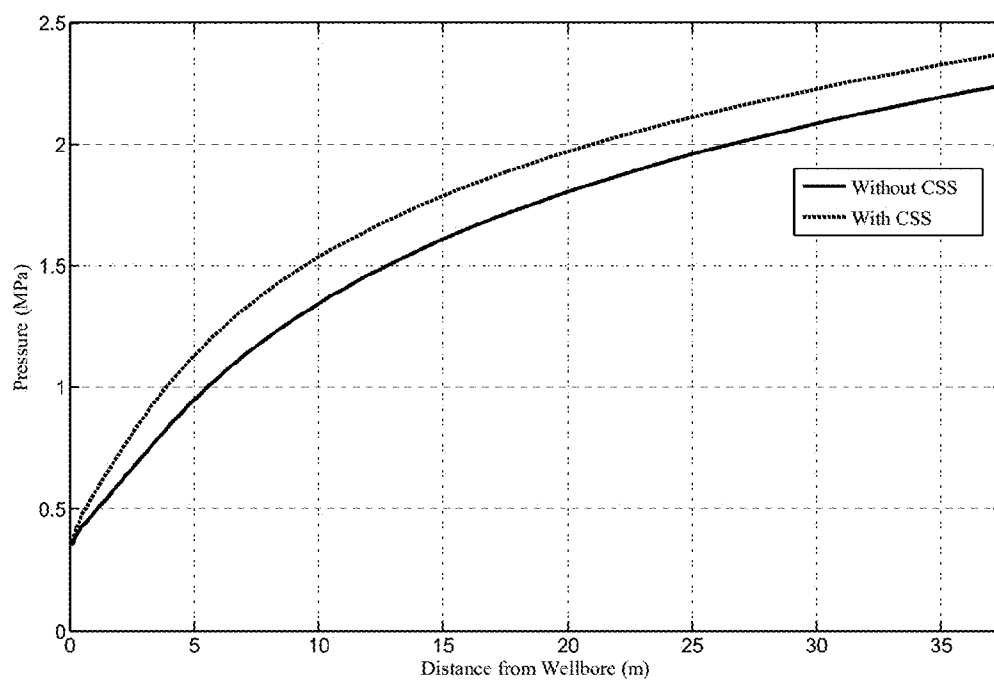


FIG. 4

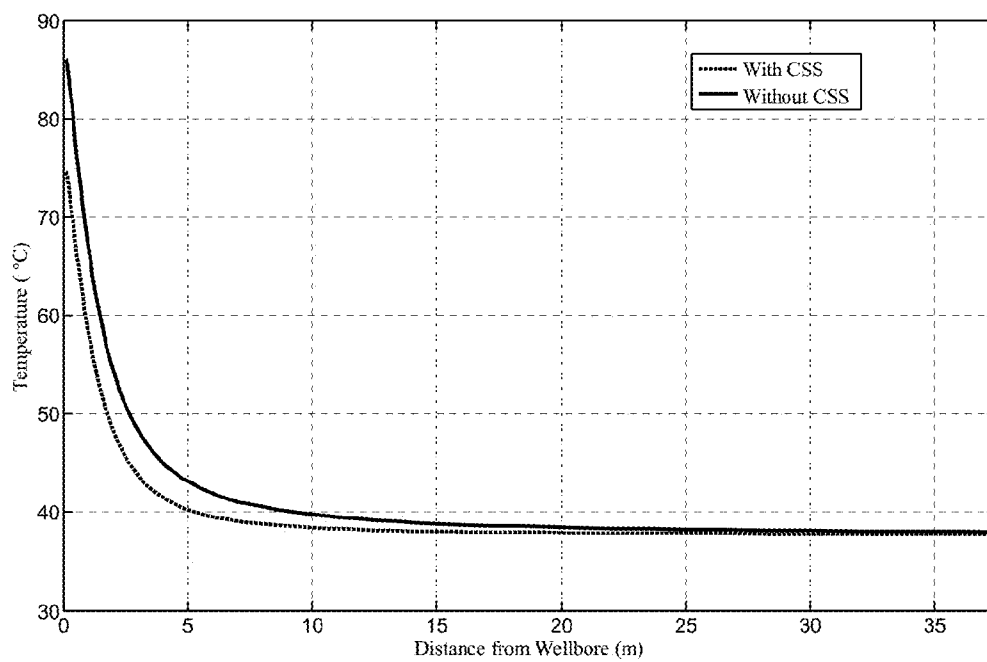


FIG. 5

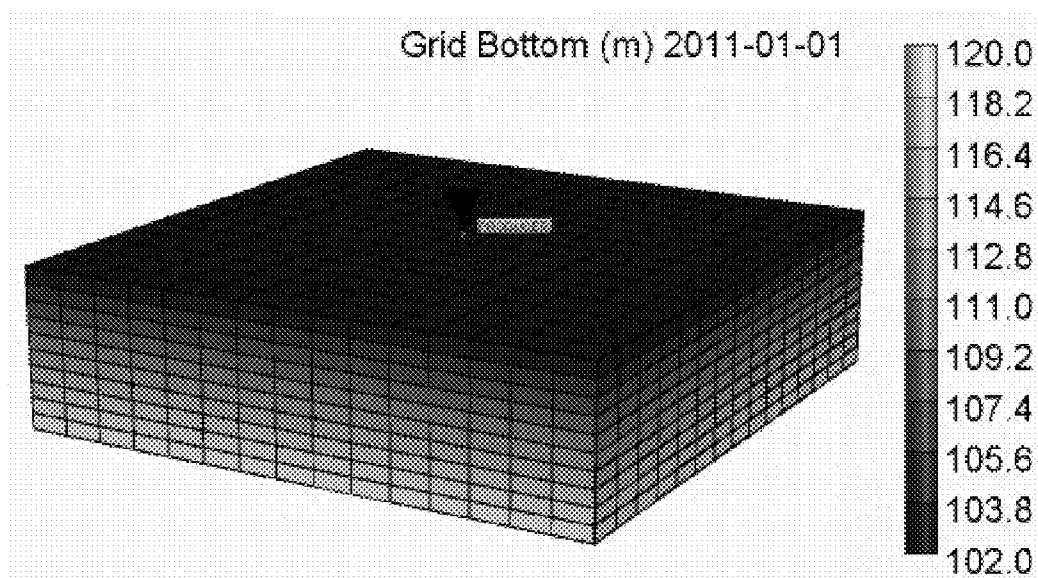


FIG. 6

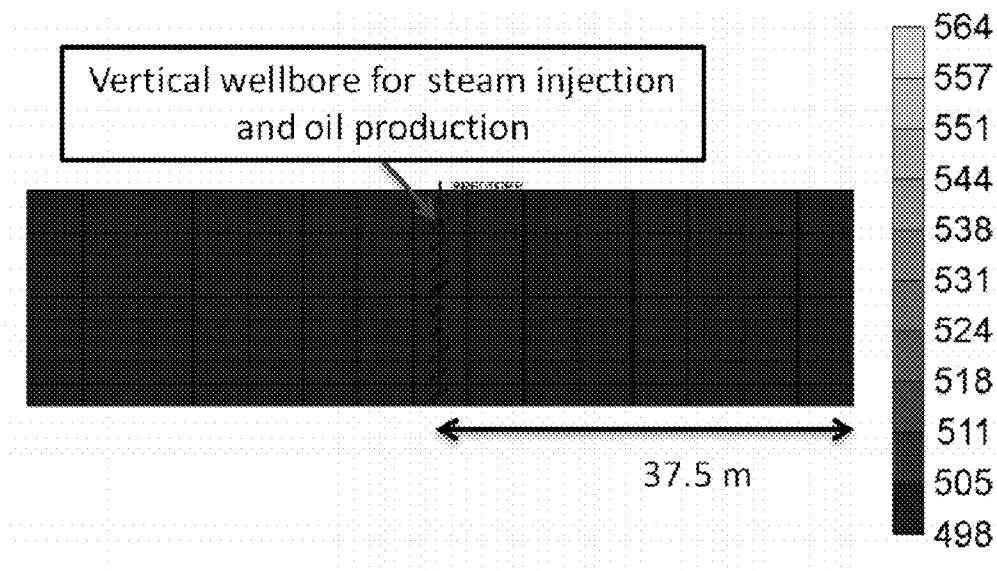


FIG. 7

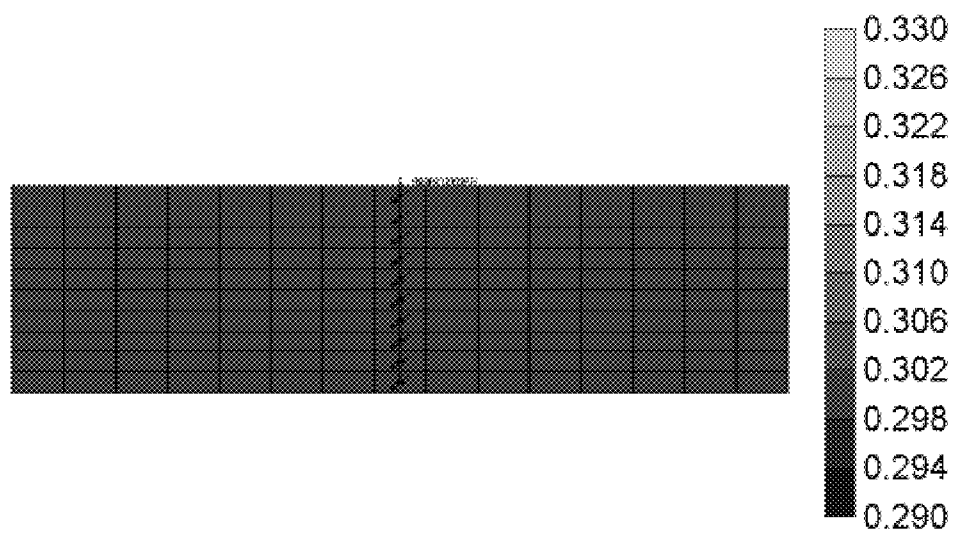


FIG. 8

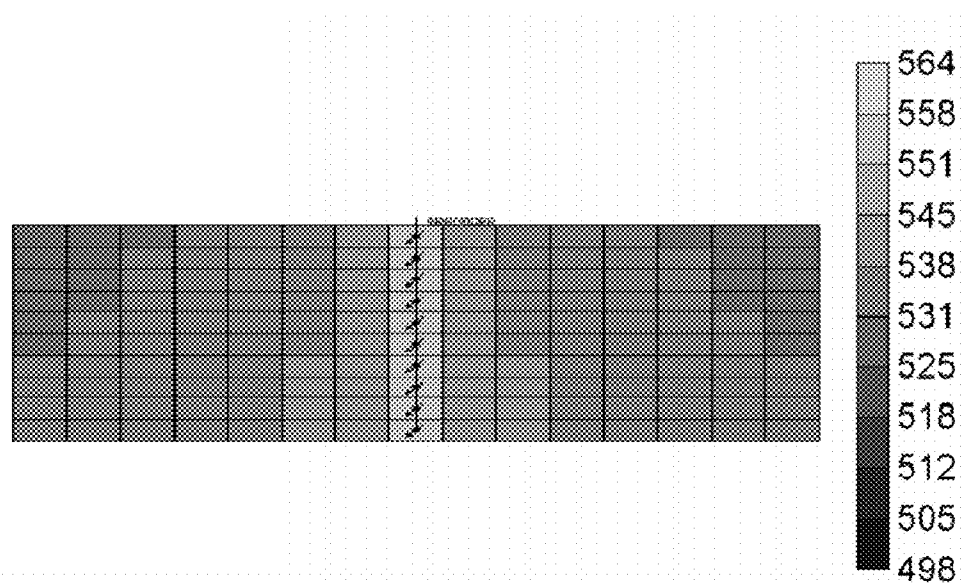


FIG. 9

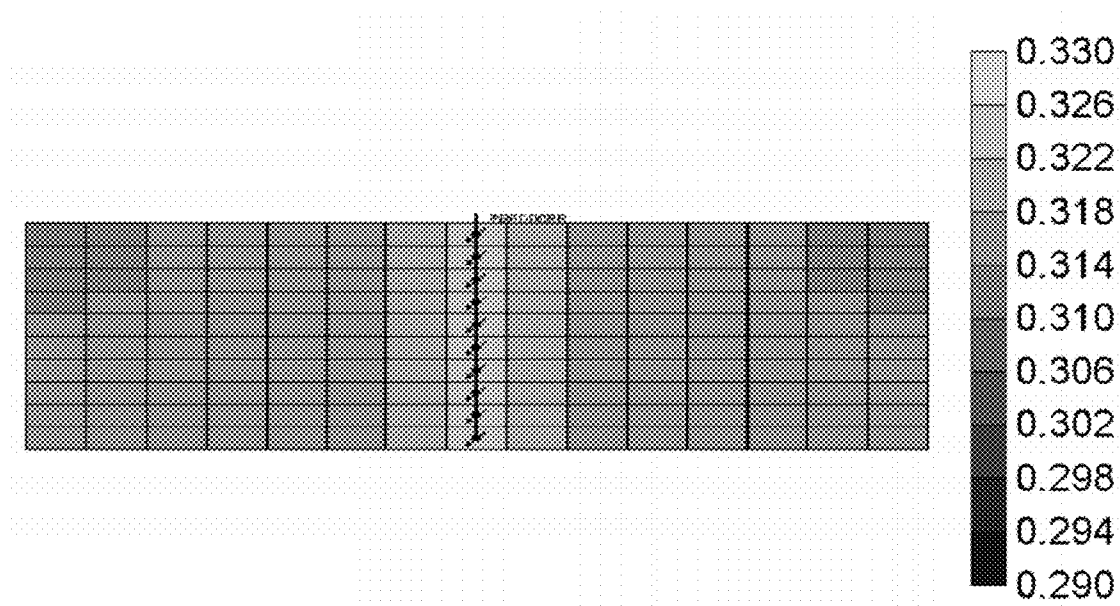


FIG. 10

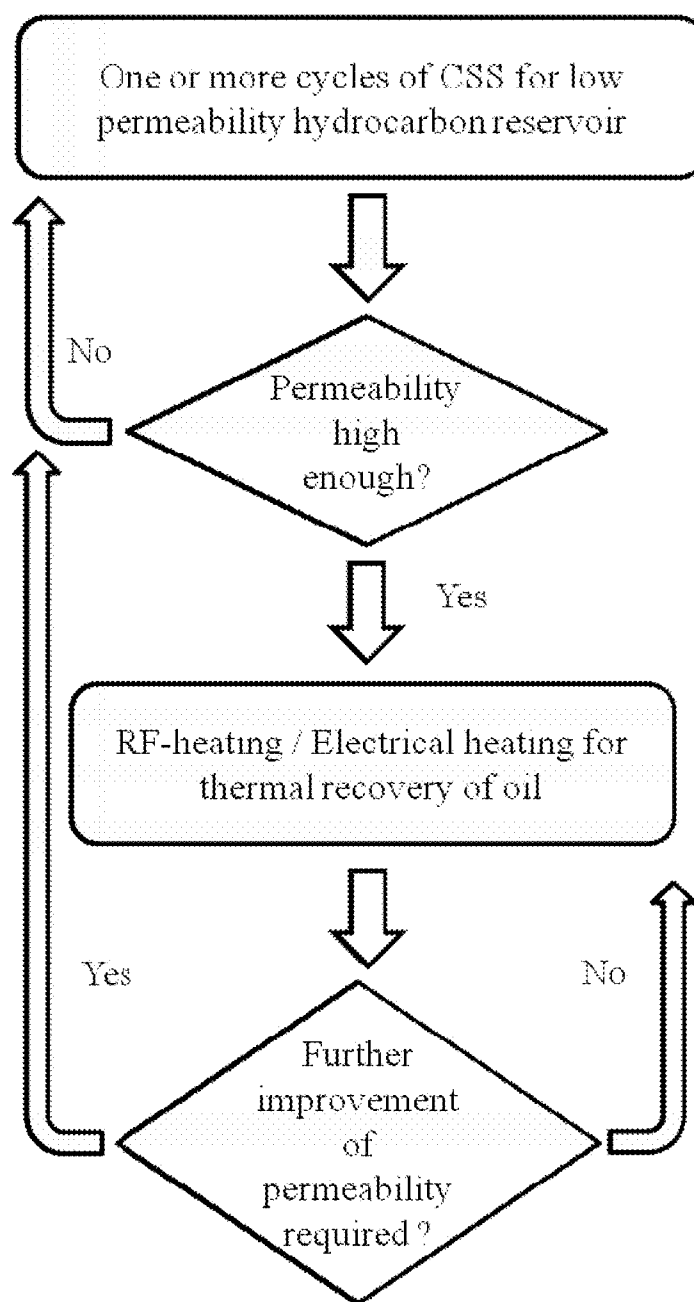
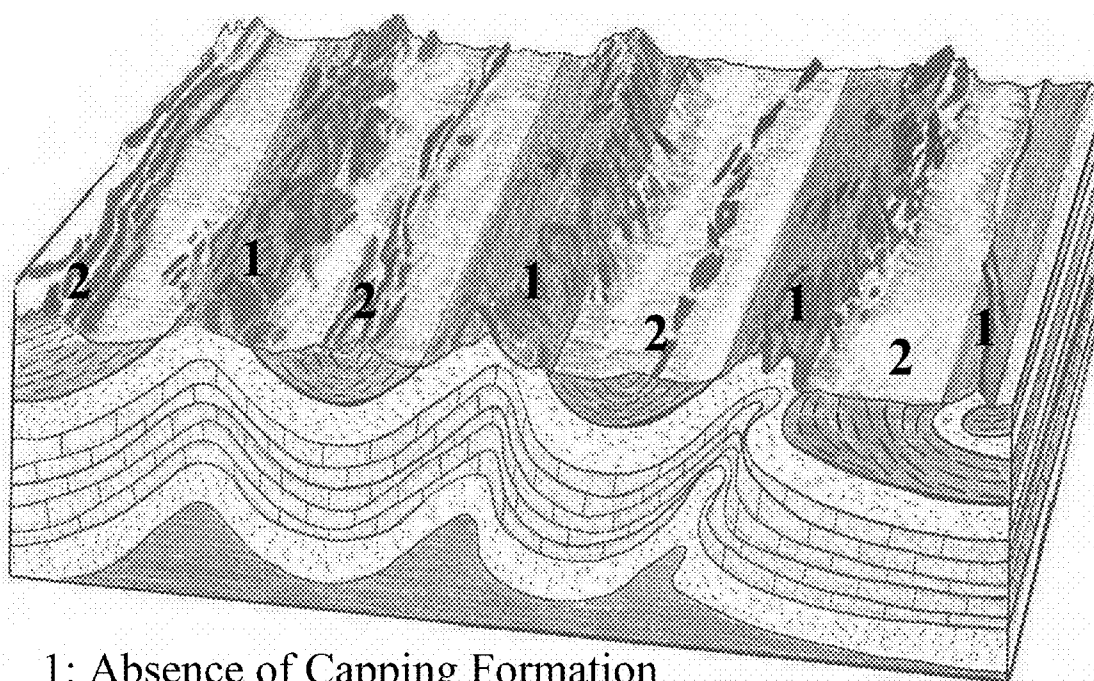


FIG. 11



1: Absence of Capping Formation

2: Good Caprock Integrity

FIG. 12

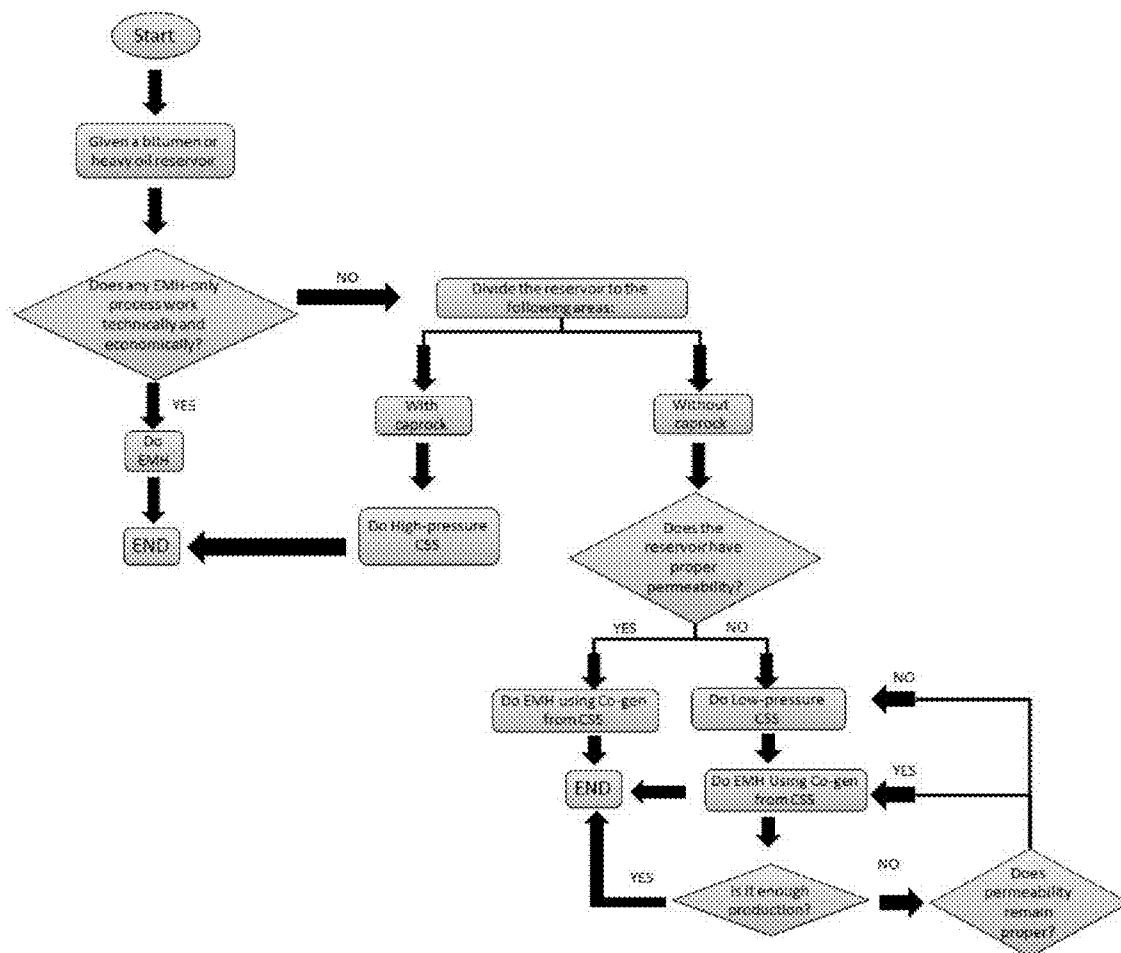
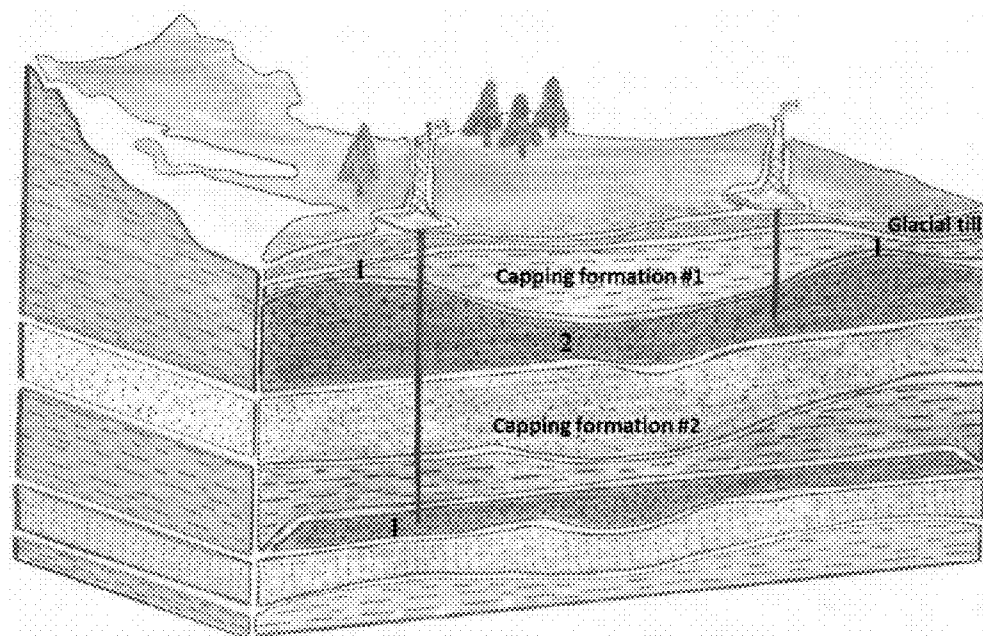


FIG. 13



1: Candidate areas for EMH

2: Candidate areas for CSS

FIG. 14

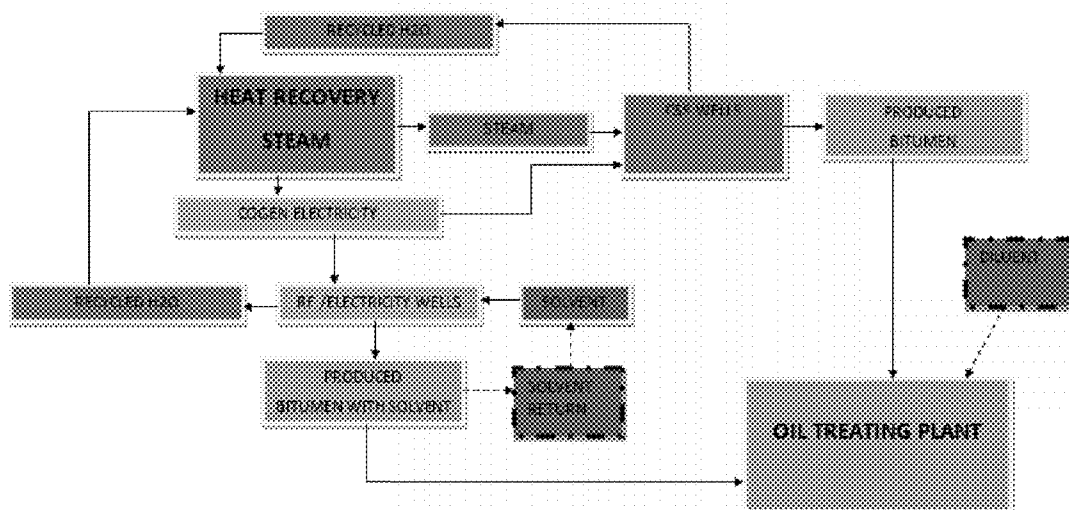


FIG. 15

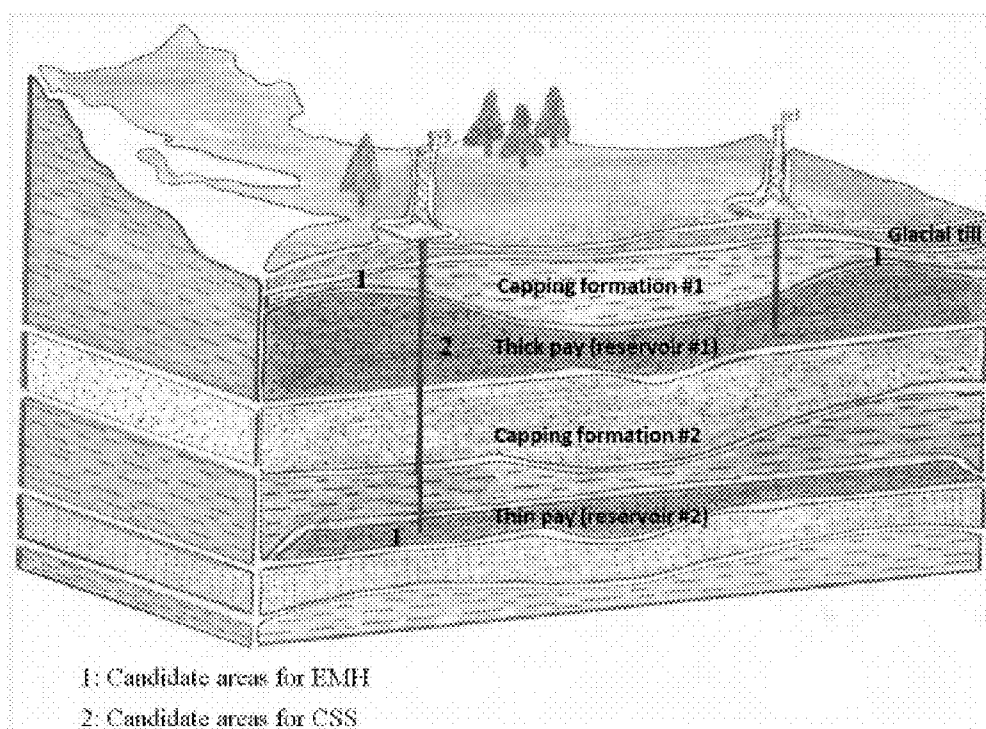


FIG. 16

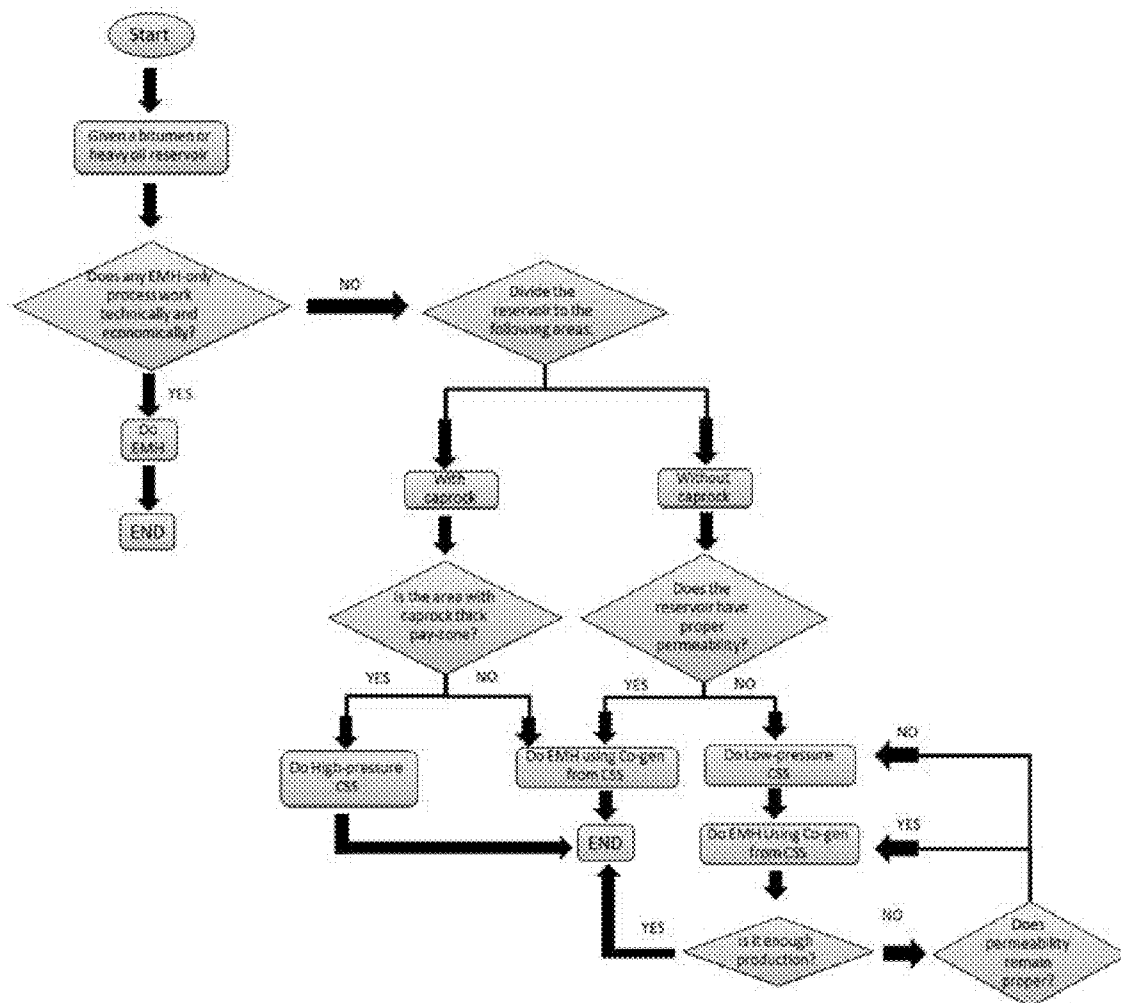


FIG. 17

METHOD FOR ENHANCED OIL RECOVERY USING CYCLIC STEAM STIMULATION AND ELECTROMAGNETIC HEATING

FIELD OF THE INVENTION

[0001] The present invention relates to hydrocarbon production methods, and specifically to thermal recovery methods.

BACKGROUND OF THE INVENTION

[0002] Heavy oil is a term commonly applied to describe oils having a specific gravity less than about 20° API. These oils, which include bitumen, are not readily producible by conventional techniques. Their viscosity is so high that the oil cannot easily be mobilized and driven to a production well by a pressure drive. Therefore, a recovery process is required to reduce the viscosity and then produce the oil.

[0003] Thermal recovery methods as applied in heavy oil have the common objective of accelerating the recovery process. Raising the temperature of the host formation reduces the heavy oil viscosity allowing the near solid material at original temperature to flow as a liquid. For heavy oil reservoirs, steam injection from the surface into the formation is used as a conventional method to heat the heavy oil in situ, reducing its viscosity to a level where the oil is amenable to displacement.

[0004] Typical methods of recovering oil from an oil sands reservoir include cyclic steam stimulation (CSS) and steam assisted gravity drainage (SAGD). Limitations of each include: CSS: This normally requires steam to be at higher pressure than a similar SAGD process. Higher pressures are used to dilate the reservoir, so this process is more forgiving than SAGD in heterogeneous reservoirs. Steam-Oil Ratios (SORs) for CSS are typically higher (ranging from 3-6) than for continuous SAGD operations, requiring more water and energy. SAGD: This is a gravity dependent process requiring high vertical permeability (>3D), a relatively thick pay zone (>10 m), a more homogeneous reservoir and higher oil saturation. SORs are typically lower for SAGD ranging from 2.0-3.0.

[0005] Both CSS and SAGD methods require high volumes of water to be converted to steam, which is energy intensive. Both CSS and SAGD may require higher pressure operations, and thus have limitations in low Maximum Operating Pressure (MOP) regimes that are found in very shallow reservoirs (but are too deep for bitumen surface mining).

[0006] There are other situations where steam injection may not work well:

[0007] Thin pay-zones, where heat losses to adjacent (non-oil-bearing) formations may be significant.

[0008] Low permeability formations, where the injected fluid may have difficulty penetrating deep into the reservoir.

[0009] Reservoir heterogeneity, where high permeability streaks or fractures may cause early injected fluid breakthrough and reduce the sweep.

[0010] Electromagnetic (EM) heating, or EMH, has been considered as a viable alternative to steam-based thermal processes.

[0011] Use of EM energy as part of in situ heavy oil production depends upon a number of factors that include: the presence of water; initial formation temperature; EM energy propagation through the formation; impedance matching and

dielectric breakdown within the formation; and changes in the dielectric response of materials at different applied frequencies. Knowledge of the frequency-specific dielectric response of the formation will allow for optimization of process parameters for pay-zone identification and recovery. Water and minerals present in the formation can affect EM energy absorption by reservoir. Both pore water saturation and mineral-bound water, in addition to mineral content, can affect the measured dielectric properties of the formation. Once these factors have been taken into consideration, EMH (a thermal process) may be applied to a well to increase its productivity by the removal of thermal adaptable skin effects and the reduction of oil viscosity near the well bore. EM-thermal recovery can manifest the following advantages compared with other recovery technologies:

[0012] Heat is generated in-situ.

[0013] It does not need a working fluid.

[0014] It does not need a significant water supply.

[0015] It reduces the produced water cut.

[0016] There is no emission concern.

[0017] There are no hazardous chemical concerns.

[0018] It can be operated at a reduced energy intensity (J/bbl are reduced).

[0019] It can operate at a lower pressure.

[0020] One limitation of EMH is that it can't run at optimal economics when reservoirs have a lower permeability, which may be found in heterogeneous reservoirs. For example, ESEIEH (Enhanced Solvent Extraction Incorporating Electromagnetic Heat) typically follows the same rules-of-thumb for operability as SAGD. This process operates at significantly lower temperatures, resulting in lower pressure, and relies on solvents to reduce the viscosity to a point where the bitumen can flow. Since it relies on gravity drainage, higher permeable reservoirs are the best application.

[0021] What is needed, therefore, is a thermal recovery method that can be used with some lower-permeability reservoirs while addressing limitations of conventional techniques such as CSS, SAGD and EMH.

SUMMARY OF THE INVENTION

[0022] The present invention therefore seeks to provide a method for first enhancing reservoir permeability, followed by an advantageous thermal recovery method.

[0023] According to a first broad aspect of the present invention, there is provided a method for recovering a hydrocarbon from a subsurface reservoir, the method comprising the steps of:

[0024] a. drilling a first well into the reservoir;

[0025] b. injecting a heated fluid through the first well into the reservoir;

[0026] c. allowing the heated fluid to heat a first portion of the hydrocarbon;

[0027] d. producing the first portion of the hydrocarbon to surface through the first well;

[0028] e. applying electromagnetic heat to the reservoir to heat a second portion of the hydrocarbon; and

[0029] f. producing the second portion of the hydrocarbon to surface.

[0030] According to a second broad aspect of the present invention, there is provided a method for recovering a hydrocarbon from a subsurface low-permeability reservoir using electromagnetic heating, the method comprising the steps of:

- [0031] a. drilling a first well into the reservoir;
- [0032] b. injecting a heated fluid through the first well into the reservoir under a pressure higher than reservoir pressure, dilating the reservoir and increasing permeability;
- [0033] c. allowing the heated fluid to heat a first portion of the hydrocarbon;
- [0034] d. producing the first portion of the hydrocarbon to surface through the first well;
- [0035] e. applying electromagnetic heat to the reservoir to heat a second portion of the hydrocarbon; and
- [0036] f. producing the second portion of the hydrocarbon to surface.

[0037] According to a third broad aspect of the present invention, there is provided a method for reducing water usage in a steam-based thermal hydrocarbon recovery technique, the method comprising the steps of:

- [0038] a. drilling a first well into a reservoir containing a hydrocarbon;
- [0039] b. injecting steam through the first well into the reservoir under a pressure higher than reservoir pressure, dilating the reservoir and increasing permeability;
- [0040] c. allowing the steam to heat a first portion of the hydrocarbon;
- [0041] d. producing the first portion of the hydrocarbon to surface through the first well;
- [0042] e. applying electromagnetic heat to the reservoir to heat a second portion of the hydrocarbon; and
- [0043] f. producing the second portion of the hydrocarbon to surface.

[0044] According to a fourth broad aspect of the present invention, there is provided a method for reducing electricity usage in an electromagnetic heat thermal hydrocarbon recovery technique, the method comprising the steps of:

- [0045] a. drilling a first well into a reservoir containing a hydrocarbon;
- [0046] b. injecting a heated fluid through the first well into the reservoir under a pressure higher than reservoir pressure, dilating the reservoir and increasing permeability;
- [0047] c. allowing the heated fluid to heat a first portion of the hydrocarbon;
- [0048] d. producing the first portion of the hydrocarbon to surface through the first well;
- [0049] e. applying electromagnetic heat to the reservoir to heat a second portion of the hydrocarbon; and
- [0050] f. producing the second portion of the hydrocarbon to surface.

[0051] According to a fifth broad aspect of the present invention, there is provided a method for increasing production of hydrocarbon in an electromagnetic heat thermal recovery technique, the method comprising the steps of:

- [0052] a. drilling a first well into a reservoir containing the hydrocarbon;
- [0053] b. injecting a heated fluid through the first well into the reservoir under a pressure higher than reservoir pressure, dilating the reservoir and increasing permeability;
- [0054] c. allowing the heated fluid to heat a first portion of the hydrocarbon;
- [0055] d. producing the first portion of the hydrocarbon to surface through the first well;
- [0056] e. applying electromagnetic heat to the reservoir to heat a second portion of the hydrocarbon; and

- [0057] f. producing the second portion of the hydrocarbon to surface.

[0058] In some exemplary embodiments of the above aspects, steps b-d are repeated at least once before applying the electromagnetic heat. Steps b-e may be repeated at least once after applying the electromagnetic heat. The electromagnetic heat may be applied by a tool situate in the first well adjacent the reservoir; alternatively, an exemplary method may further comprise the step of drilling a second well into the reservoir, wherein the electromagnetic heat is applied by a tool situate in the second well and at least a part of the second portion of the hydrocarbon is produced to surface through the second well.

[0059] The electromagnetic heat may be either liner/casing conveyed or reservoir conveyed. In the former, the electromagnetic heat may be from a source selected from the group consisting of a resistive heat and induction heat. In the latter, the electromagnetic heat may be from a source selected from the group consisting of resistive AC/low frequency, induction heat, radiofrequency (RF) radiation heat and microwave radiation heat. The electromagnetic heat may also be applied with at least one viscosity reducing agent known to those skilled in the art.

[0060] A detailed description of exemplary embodiments of the present invention is given in the following. It is to be understood, however, that the invention is not to be construed as being limited to these embodiments.

BRIEF DESCRIPTION OF THE DRAWINGS

[0061] In the accompanying drawings, which illustrate exemplary embodiments of the present invention:

[0062] FIG. 1A is a simplified section view of a subsurface environment, illustrating a state before application of the within recovery techniques;

[0063] FIG. 1B is a simplified section view of the subsurface environment of FIG. 1A, with an injector/producer well drilled into the reservoir;

[0064] FIG. 1C is a simplified section view of the subsurface environment of FIG. 1A, illustrating the effect of a series of CSS injection and production cycles;

[0065] FIG. 1D is a simplified section view of the subsurface environment of FIG. 1A, illustrating the onset of exemplary EM heating from the same CSS well;

[0066] FIG. 2 is a simplified section view of a combined CSS-RF wellbore configuration, as an example of the general CSS-EMH process;

[0067] FIG. 3 is a chart illustrating a reservoir deformation model;

[0068] FIG. 4 is a chart illustrating steady-state pressure after RF heating;

[0069] FIG. 5 is a chart illustrating steady-state temperature after RF heating;

[0070] FIG. 6 is an illustration of a reservoir model;

[0071] FIG. 7 is an illustration of reservoir initial permeability;

[0072] FIG. 8 is an illustration of reservoir initial porosity;

[0073] FIG. 9 is an illustration of improved reservoir permeability after CSS;

[0074] FIG. 10 is an illustration of improved reservoir porosity after CSS;

[0075] FIG. 11 is a flowchart illustrating an exemplary method according to the present invention;

[0076] FIG. 12 is a section view of a target area having alternating areas of good caprock integrity and absence of caprock;

[0077] FIG. 13 is a flowchart illustrating an embodiment of the present invention where caprock presence/integrity is under consideration;

[0078] FIG. 14 is a section view of strata illustrating areas to target with discrete CSS and EMH wells;

[0079] FIG. 15 is a simplified process flow diagram for discrete CSS and RF wells with integration of cogeneration;

[0080] FIG. 16 is a section view of strata illustrating areas to target with discrete CSS and EMH wells; and

[0081] FIG. 17 is a flowchart illustrating the use of an embodiment of the present invention with a reservoir having thick and thin pay zones.

[0082] Exemplary embodiments of the present invention will now be described with reference to the accompanying drawings.

DETAILED DESCRIPTION OF EXEMPLARY EMBODIMENTS

[0083] Throughout the following description specific details are set forth in order to provide a more thorough understanding to persons skilled in the art. However, well known elements may not have been shown or described in

CSS acts to assist the EMH recovery method by preparing the reservoir and may thus enhance the utility of the EMH recovery method in appropriate reservoirs. Those skilled in the art will be readily able to determine whether a particular reservoir is appropriate for application of the present invention and exemplary embodiments set forth herein.

[0085] In essence, exemplary embodiments according to the present invention begin with a single conventional CSS injection-production cycle, with operating parameters selected in order to produce the desired reservoir rock dilation effect. One or more CSS cycles may follow, depending on the reservoir and any other relevant factors identified by the skilled person. After completion of the one or more CSS cycles, an EMH thermal recovery technique is applied, thus reducing water and energy usage when compared with conventional CSS alone.

[0086] Various cycle combination can be considered for implementation, again depending on the reservoir and any other relevant factors identified by the skilled person. For example, a single CSS cycle may be followed by an EMH application, followed again by a single CSS cycle and EMH application. Alternatively, two or more CSS cycles may be conducted in series, followed by EMH application.

[0087] EMH as applied in exemplary embodiments of the present invention may take any number of forms, as set forth in Table 1.

TABLE 1

EMH Methods	
Liner or Casing Conveyed	
Resistive Heating Element	Conduction through liner or casing. Heat penetration is time dependent. EM energy converts to thermal energy in the heating element.
Induction Heat	Conduction through liner or casing. Heat penetration is time dependent. EM energy used to induce eddy current flow in the well casing that creates thermal energy.
Reservoir Conveyed	
Resistive AC/Low Frequency e.g. 50 or 60 Hz	Formation electrical resistance via ionic conduction When low frequency AC current is used, it is considered resistive or ohmic heating
Induction Heat e.g. in the range from 300 Hz-300 kHz	Electromagnetic energy used to induce eddy current flow in the reservoir that creates thermal energy through electrical resistance
RF Radiation Heating e.g. in the range from 300 kHz-300 MHz	Dielectric absorption (like microwave but at lower frequency) Faster heating process compared to previous types of EM-thermal mechanisms Instant heat penetration for a few tens of meters between wells at 1 MHz, depending on electrical properties of the reservoir RF Energy preferentially heats the target polar molecules such as water, oil, contaminants preferably to the host (OB and Rock)
Microwave Radiation Heating e.g. in the range from 300 MHz to 300 GHz	Dielectric absorption Instant heat penetration up to a few meters maximum but with greater heat rate compared to RF-heating

detail to avoid unnecessarily obscuring the disclosure. The following description of examples of the invention is not intended to be exhaustive or to limit the invention to the precise forms of any exemplary embodiment. Accordingly, the description and drawings are to be regarded in an illustrative, rather than a restrictive, sense.

[0084] The present invention is directed to methods in which one or more CSS cycles are performed on a formation of interest, in order to dilate the reservoir rock and thus improve permeability, which results in a reservoir more amenable to EMH techniques such as RF thermal recovery. Thus, unlike conventional CSS recovery methods where CSS is the primary or only technique employed, in the present invention

[0088] In some exemplary embodiments of the present invention, EMH can be employed and used with or without viscosity reducing agents such as solvents, gas condensate, diluents or combinations thereof, while the use of steam is optional. One skilled in the art will recognize that the above ranges are examples and one can easily adopt the proper frequency to adapt to the intended application. It can also be used in a variety of well configurations; horizontal, vertical, inclined and directional.

[0089] Turning now to FIGS. 1A, 1B, 1C and 1D, a first exemplary method is illustrated. FIG. 1A illustrates the state of a reservoir 10 before recovery begins. Termed Phase "0", the bitumen/heavy oil reservoir 10 is situate underneath a cap

rock **12**, with surrounding rock layers above and below. In FIG. 1B illustrating Phase “1” of recovery, an injector/producer well **14** is drilled through the overburden **16** and cap rock **12** into the reservoir rock **10**. Perforations **18** are generated in a conventional manner to allow flow of hydrocarbon into the well **14**, and an EMH tool (not shown, but illustrated in FIG. 2) is positioned in the bitumen/heavy oil bearing layer of the well **14**. While perforations **18** are illustrated, it will be obvious to one skilled in the art that other suitable means of providing apertures are possible to allow passage of fluids across the casing and therefore are intended to fall within the scope of the present invention. While a vertical well is shown, the well could be vertical or horizontal, as would be obvious to those skilled in the art.

[0090] In FIG. 1C illustrating Phase “2”, a series of CSS injection and production cycles is initially performed in order to create some voidage in the reservoir **10** and to create a high-temperature, low bitumen/heavy oil viscosity zone **20** around the wellbore. This zone **20** is a steam-heated zone adjacent the wellbore and EMH tool. At this point, where a desirable steam zone **20** has been prepared, traditional CSS operations will be paused.

[0091] In FIG. 1D illustrating Phase “3”, EM-heating begins, injecting heat at a specific and selected power and frequency and allowing production of bitumen/heavy oil from the zone **20** previously heated using CSS. EMH operations will be paused when the bitumen/heavy oil production rate is below a certain determined rate, and at this point a number of CSS cycles may again be performed in order to increase the size of the steam-heated zone **20**, following which EMH operations can recommence. The alternating CSS-EMH process will cease once a determined economical limit is reached. Note that the RF (radio frequency) heating may be paused during production or alternatively remain active during production.

[0092] To illustrate the potential enhancement of EMH methods by using CSS dilation of the reservoir, modeling was conducted for RF-thermal recovery of heavy oil/bitumen. RF-heating is selected for this purpose because it takes the complete form of the electromagnetic model (Maxwell's equations) of the EMH into account. Similar methodology can be employed for other types of EMH by using approximate representations of electromagnetic governing equations. A simplified steady-state model of coupled electromagnetic-transport phenomena is developed and solved semi-analytically below to show the effect of improved permeability in the RF-thermal recovery using a CSS-dilation mechanism.

[0093] Starting with the electromagnetic aspect and considering time-harmonic Maxwell's equations in a homogeneous medium yields the wave equation for the electric-field written as:

$$\nabla^2 E + \gamma^2 E = 0 \quad (1)$$

$$\gamma = \omega \sqrt{\mu_0 \epsilon_0 \left(\epsilon' - j \left(\epsilon'' + \frac{\sigma}{\omega} \right) \right)}$$

where ω , μ_0 , ϵ_0 , $\epsilon' - j\epsilon''$, σ , are the angular frequency, magnetic permeability of vacuum, electrical permittivity of vacuum, relative complex permittivity of reservoir, and electrical conductivity of the reservoir, respectively. It should be noted that the temperature dependency of relative complex permittivity

and electrical conductivity of the reservoir has been neglected here for simplicity, which is consistent with using a classical wave equation in homogenous medium shown in (1).

[0094] Now, employing an RF antenna (electromagnetic radiating source) in a vertical or horizontal wellbore in the same configuration as a vertical or horizontal CSS process (illustrated in FIG. 2 for a vertical wellbore as an example), assuming only radial dependency, i.e., axisymmetrical and depth-invariant condition, or mathematically,

$$\frac{\partial}{\partial \varphi} = \frac{\partial}{\partial z} = 0, \quad (1)$$

will have the following analytical solution:

$$E = A_+ H_0^{(2)}(\gamma r) \quad (2)$$

where $H_0^{(2)}$ is the Hankel function of the second kind of order zero and A_+ is constant determined by the radiation input power. Using Poynting's theorem yields the time-average dissipated electromagnetic power density in the following form:

$$\dot{Q}_{EM} = \frac{1}{2} (\omega \epsilon'' + \sigma) |E|^2 \quad (3)$$

[0095] It should be mentioned again that the proposed technique is not limited to vertical boreholes and can be applied to horizontal wellbores, as well.

[0096] For the transport phenomenon aspect of the model, conservation of energy, conservation of mass, and Darcy's equations under steady-state and single-phase fluid flow conditions are coupled and yield:

$$\begin{cases} \nabla \cdot (\lambda \nabla T) + M_f \frac{k}{\mu} \nabla p \cdot \nabla T + \dot{Q}_{EM} = 0 \\ \nabla \cdot \left(\frac{k}{\mu} \nabla p \right) = 0 \end{cases} \quad (4)$$

where

$$\begin{cases} \phi = \phi_r e^{c_p(p-p_r)} \\ k = k_0 e^{\frac{\phi - \phi_0}{1 - \phi_0}} \\ \mu = D e^{\frac{F}{T}} \end{cases} \quad (5)$$

[0097] In (4) T and p are temperature and pressure, respectively. Also, λ , M_f , k , μ are thermal conductivity, volumetric heat capacity of the fluid, reservoir permeability and fluid viscosity, respectively. Equations in (5) represent dilation effect (through CSS) on permeability and formation porosity, ϕ , as well as the temperature dependency of the fluid (in this case heavy oil/bitumen) viscosity. Also, k_0 , ϕ_0 , k_M , ϕ_r , c_p , D , and F are original permeability and porosity, a multiplier constant for permeability after dilation, porosity at a reference pressure p_r , pore volume compressibility, and empirical constants for the viscosity correlation.

[0098] Now, according to the proposed workflow, first one or a few cycles of CSS are carried out followed by the RF-thermal process. The reservoir deformation model of dila-

tion-recompaction is shown in FIG. 3, which is a reservoir deformation model during a CSS process, from the CMG-STARS Manual.

[0099] The exemplary methodology takes advantage of the dilation part of deformation by starting the RF-thermal recovery at the end of the dilation part of the CSS process. The proposed multi-physics model takes the porosity at the end of the dilation branch of the deformation curve ($f_r=1$ or $A=B$, in FIG. 3) as the constant values for porosity and permeability during the production-recompaction period. Now, assuming only radial dependency, (4) is simplified to the following form:

$$\begin{cases} \frac{\lambda}{r} \frac{dT}{dr} + \lambda \frac{d^2 T}{dr^2} + M_f \frac{k_{max}}{\mu} \frac{dT}{dr} \frac{dp}{dr} + \dot{Q}_{EM} = 0 \\ \frac{1}{r} \frac{dp}{dr} + \frac{d^2 p}{dr^2} + \frac{F}{T^2} \frac{dT}{dr} \frac{dp}{dr} = 0 \end{cases} \quad (6)$$

where

$$\begin{cases} \phi_{max} = \phi_r e^{\epsilon p(p_{max}-p_r)} \\ k_{max} = k_0 e^{\frac{k_M}{1-\phi_0} (\phi_{max}-\phi_0)} \end{cases} \quad (7)$$

with the following boundary conditions:

$$\begin{cases} T|_{r \rightarrow \infty} = T_0 \\ p|_{r=r_w} = p_b \\ p|_{r \rightarrow \infty} = p_0 \\ \left. \frac{dT}{dr} \right|_{r=r_w} = 0 \\ \left. \frac{dT}{dr} \right|_{r \rightarrow \infty} = 0 \end{cases} \quad (8)$$

[0100] The system of nonlinear ordinary differential equations in (6) can be solved semi-analytically using the shooting method, which is based on converting the boundary value problem (BVP) into an equivalent initial value problem (IVP). The obtained IVP is then solved by the Runge-Kutta method using a generic set of parameters considered in Table 2 below. In (7) and (8), p_{max} , T_0 , p_b , r_w , and p_0 are the maximum reservoir pressure due to steam injection (CSS), initial reservoir temperature, bottom hole pressure during the production period, wellbore radius and initial reservoir pressure, respectively.

TABLE 2

Φ	0.3
ρ_f	1020 (kg/m ³)
c_f	2.09 (kJ/kg/K)
$M_f = \rho_f c_f$	2131.8 (kJ/m ³ /K)
D	2.2×10^{-6} (cp)
F	6611.7 (K)
$f = \omega/(2\pi)$	2 (MHz)
H (pay-zone thickness)	20 (m)
ϵ'	10
ϵ''	0.5
σ	0.06 (S/m)
μ_0	$4\pi \times 10^{-7}$ (H/m)
ϵ_0	$1/(36 \times \pi) \times 10^{-9}$ (F/m)
$\Phi_r = \phi_0$	30%
c_p	4.5×10^{-5} (1/kPa)
p_{max}	9277 (kPa)

TABLE 2-continued

p_r	3447 (kPa)
k_0	500 (mD)
k_M	3
T_0	37.7 (° C.)
p_b	350 (kPa)
p_0	3447 (kPa)
r_w	0.1 (m)

[0101] The results of the semi-analytical modeling are shown in FIGS. 4 and 5 where steady-state pressure and temperature are depicted for RF-thermal process with and without prior CSS operation. It can be observed that for an equal RF input power, the overall steady-state pressure for the case of CSS combined with RF-thermal process is higher than that of an RF-thermal process without CSS due to the higher permeability created by steam injection and consequently greater fluid flow, and for this same reason, the steady-state temperature is also lower for the coupled CSS-RF heating process intuitively due to the flowing heat convection and smoother thermal exchange in the reservoir. Furthermore, given the same input RF power and the reservoir parameters presented in Table 2, it was found that the production rate is increased by 30% by using coupled CSS-RF, calculated by

$$Q = 2\pi r H \frac{k}{\mu(T)} \frac{dp}{dr} \bigg|_{r=r_w} \quad (9)$$

[0102] The same reservoir model was adopted for a complete CSS process simulation using CMG-STARS. The reservoir model is illustrated in FIG. 6, which is a model of a 75 m×75 m×20 m reservoir using CMG-STARS, with depth in meters. Initial permeability is illustrated in FIG. 7 (in mD, with a 500 mD homogenous permeability assumption), and initial porosity is illustrated in FIG. 8 (with a 30% homogenous porosity assumption (fractions)).

[0103] FIG. 9 illustrates the permeability improvement after 9 months of steam injection before applying RF heat for thermal recovery (in mD), showing an increase from 500 mD to a maximum value of 564 mD. FIG. 10 illustrates the porosity improvement after 9 months of steam injection before applying RF heat for thermal recovery, showing an increase (fraction) from 30% to a maximum of 33%.

[0104] Although RF heating is utilized in the above simulation exercise, it will be obvious to those skilled in the art that this method may have utility with other frequency ranges.

[0105] FIG. 11 illustrates an exemplary CSS-assisted RF-thermal recovery method in accordance with the present invention. After one or more CSS cycles have been applied to a low-permeability reservoir, a determination is made as to whether the permeability has been enhanced to a desired level. If the answer is yes, EMH thermal recovery can begin; if the answer is no, further CSS cycles may be applied to the reservoir. After EMH application, it may be determined that further permeability enhancement is desirable, in which case the process would loop back to one or more additional CSS cycles followed by EMH thermal recovery.

[0106] While higher pressure CSS may be employed where appropriate to dilate the reservoir rock to enhance EMH methods, it is known to those skilled in the art that certain formations may not be suitable for such higher pressure injection methods. It is known that in any project area where heavy

oil or bitumen reservoirs are found, there are usually areas that require recovery methods other than CSS due to lower maximum operating pressure (MOP) limitations. This is due to the absence of a capping formation leaving areas of the project un-producible using CSS. See FIG. 12, for example, which illustrates a situation where areas marked with the numeral 1 manifest an absence of caprock and thus are not appropriate candidates for CSS, whereas the areas marked with the numeral 2 are provided with sufficient caprock coverage.

[0107] According to a further exemplary embodiment of the present invention, then, and unlike the embodiment of FIGS. 1A-1D where a single CSS-EMH well was used, an exemplary hydrocarbon recovery system is disclosed in which CSS and EMH wells are discrete but integrated, optionally also including the use of cogeneration to reduce costs. Turning now to FIG. 13, such a further exemplary method is illustrated. In this case, if EMH alone is feasible the resource can be extracted using that conventional method. If it is not, then it must be determined whether suitable caprock integrity is present for the target formation. Where there is suitable caprock integrity, the above-described alternation of CSS cycles and EMH may be employed. However, where caprock is absent or inadequate, a determination is made as to whether the reservoir permeability is suitable for conventional EMH (in which case that can be considered for implementation, including possibly cogeneration, as described below) or is insufficient.

[0108] If the permeability is insufficient for conventional EMH thermal recovery methods, but the caprock integrity makes higher-pressure CSS unsuitable, the exemplary embodiment incorporates the use of low-pressure CSS. The exact pressures involved will obviously depend on a variety of factors, primarily relating to the reservoir itself and the surrounding formations, as would be known to those skilled in the art. Low-pressure CSS cycles can be repeated as necessary to dilate the reservoir and make EMH (with or without cogeneration support) a viable thermal recovery method.

[0109] As suggested above, the amount of electricity required for EMH may also present a disadvantage in certain contexts. Hence, the cost of running electrical heaters may be undesirably high depending on the number of wells in production in a given reservoir and the power requirements. Further, often in remote areas a reliable power supply is not readily available. By introducing cogeneration as part of the full-field development, the operational costs may be significantly reduced. The electricity produced at the steam plant can power both the EMH cycles in the CSS-EMH wells, as well as those areas/pay zones that can only be produced using EMH. Turning to FIG. 14, candidate areas for EMH are labeled by the numeral 1, whereas candidate areas for CSS are labeled by the numeral 2.

[0110] Electricity produced on-site has two major advantages:

[0111] Steady and reliable power is produced, thus reducing the risk of a plant shutdown due to power grid interruptions; and

[0112] Electricity produced by natural gas-run cogeneration units has a reduced environmental footprint when compared to coal-fired power plants, thus reducing overall greenhouse gas emissions.

[0113] EMH recovery methods, including the addition of solvents, are effective in areas with compromised cap rock integrity, thus requiring lower maximum operating tempera-

tures. EMH can be operated at or near reservoir pressures and still be effective in vaporizing solvents for added drive and viscosity reduction. By using power generated at site, production costs may be substantially lowered. For example:

[0114] A 30,000 bbl/day CSS project with cogeneration may generate 4,195 MWh/day.

[0115] This same project will demand 300 MWh/day for day-to-day operations.

[0116] 3,895 MWh/d can be used to operate the EMH wells.

[0117] An EMH well (either RF or electrical heating cables) will demand between 5-10 MWh/day of energy taking into consideration efficiency of the system and subsurface line losses.

[0118] Thus, a 30,000 bbl/day CSS project with cogeneration could potentially provide enough power for more than 390 wells.

[0119] Further field efficiency can be found in combining the solvent/diluent into a singular gas condensate, reducing the amount of solvent return equipment and using the diluent in the EMH process.

[0120] Turning now to FIG. 15, an exemplary system according to the present invention is illustrated. Note that the system includes both CSS wells (for producing hydrocarbon using traditional CSS methods) and RF/electricity wells (for producing hydrocarbon using RF or electricity-generated heat to mobilize the hydrocarbon). In the exemplary system, the CSS wells are provided with steam from a heat recovery steam unit. The CSS wells produce water which can be recycled for use in the heat recovery steam unit. The CSS wells also produce bitumen (in the illustrated example), which may be selectively blended with diluent at an oil treating plant. The heat recovery steam unit can also be used to produce electricity through a conventional cogeneration facility, as would be known to those skilled in the art. This produced electricity is then used to power the RF/electricity wells to produce bitumen which is sent to the oil treating plant. Solvent can be added to the RF/electricity production process, in a conventional manner, and returned to the supply source after production. The RF/electricity wells will also produce water that can be recycled for use in the heat recovery steam unit. It will be obvious to those skilled in the art that additional inputs such as electricity and/or heat will be required, but the use of cogeneration will substantially reduce the electrical costs of the facility and the environmental footprint. The overall EROI (Energy Return on Investment) is increased as both steam and electricity are harnessed to produce bitumen.

[0121] Turning to yet a further exemplary embodiment, it is known that CSS also has limited application in thin pay zones. In thin pay zones, a greater percentage of the useful heat is lost than in the case of thicker zones when the heat is warming a greater thickness of bitumen. This loss to overburden translates to higher operating costs. Thin bodies may also have reduced oil saturation, further reducing economic viability. In some areas, both thick zones (where CSS is feasible) and thin zones (where CSS is not feasible) are stacked, as can be seen in FIG. 16.

[0122] In such a situation, exemplary embodiments according to the present invention may be advantageous. Turning to FIG. 17, a flowchart illustrates an exemplary method for use with situations where thick and thin pay zones may be present. Where EMH cannot be feasibly employed on its own, the reservoir is divided into areas with caprock and areas

without caprock. For areas without caprock, the above description with respect to the similar steps of FIG. 13 is applicable. For areas with caprock, a determination is made as to whether the area with caprock is a thick pay zone; if so, high-pressure CSS can be employed; if not, the area may be produced using EMH since losses to the overburden are reduced and the process may be economic.

[0123] As will be clear from the above, those skilled in the art would be readily able to determine obvious variants capable of providing the described functionality, and all such variants and functional equivalents are intended to fall within the scope of the present invention.

[0124] Specific examples have been described herein for purposes of illustration. These are only examples. The technology provided herein can be applied to contexts other than the exemplary contexts described above. Many alterations, modifications, additions, omissions and permutations are possible within the practice of this invention. This invention includes variations on described embodiments that would be apparent to the skilled person, including variations obtained by: replacing features, elements and/or acts with equivalent features, elements and/or acts; mixing and matching of features, elements and/or acts from different embodiments; combining features, elements and/or acts from embodiments as described herein with features, elements and/or acts of other technology; and/or omitting combining features, elements and/or acts from described embodiments.

[0125] The foregoing is considered as illustrative only of the principles of the invention. The scope of the claims should not be limited by the exemplary embodiments set forth in the foregoing, but should be given the broadest interpretation consistent with the specification as a whole.

1. A method for recovering a hydrocarbon from a subsurface reservoir, the method comprising the steps of:

- a. drilling a first well into the reservoir;
- b. injecting a heated fluid through the first well into the reservoir;
- c. allowing the heated fluid to heat a first portion of the hydrocarbon;
- d. producing the first portion of the hydrocarbon to surface through the first well;
- e. applying electromagnetic heat to the reservoir to heat a second portion of the hydrocarbon; and
- f. producing the second portion of the hydrocarbon to surface.

2. The method of claim 1 further comprising repeating steps b-d at least once before applying the electromagnetic heat.

3. The method of claim 1 further comprising repeating steps b-e at least once after applying the electromagnetic heat.

4. The method of claim 1 wherein the electromagnetic heat is applied by a tool situate in the first well adjacent the reservoir.

5. The method of claim 1 further comprising the step of drilling a second well into the reservoir, wherein the electromagnetic heat is applied by a tool situate in the second well and at least a part of the second portion of the hydrocarbon is produced to surface through the second well.

6. The method of claim 1 wherein the electromagnetic heat is liner/casing conveyed.

7. The method of claim 1 wherein the electromagnetic heat is reservoir conveyed.

8. The method of claim 6 wherein the electromagnetic heat is from a source selected from the group consisting of a resistive heat and induction heat.

9. The method of claim 7 wherein the electromagnetic heat is from a source selected from the group consisting of resistive AC/low frequency, induction heat, radiofrequency radiation heat and microwave radiation heat.

10. The method of claim 1 wherein the electromagnetic heat is applied with at least one viscosity reducing agent.

11. A method for recovering a hydrocarbon from a subsurface low-permeability reservoir using electromagnetic heating, the method comprising the steps of:

- a. drilling a first well into the reservoir;
- b. injecting a heated fluid through the first well into the reservoir under a pressure higher than reservoir pressure, dilating the reservoir and increasing permeability;
- c. allowing the heated fluid to heat a first portion of the hydrocarbon;
- d. producing the first portion of the hydrocarbon to surface through the first well;
- e. applying electromagnetic heat to the reservoir to heat a second portion of the hydrocarbon; and
- f. producing the second portion of the hydrocarbon to surface.

12. The method of claim 11 further comprising repeating steps b-d at least once before applying the electromagnetic heat.

13. The method of claim 11 further comprising repeating steps b-e at least once after applying the electromagnetic heat.

14. The method of claim 11 wherein the electromagnetic heat is applied by a tool situate in the first well adjacent the reservoir.

15. The method of claim 11 further comprising the step of drilling a second well into the reservoir, wherein the electromagnetic heat is applied by a tool situate in the second well and at least a part of the second portion of the hydrocarbon is produced to surface through the second well.

16. The method of claim 11 wherein the electromagnetic heat is liner/casing conveyed.

17. The method of claim 11 wherein the electromagnetic heat is reservoir conveyed.

18. The method of claim 16 wherein the electromagnetic heat is from a source selected from the group consisting of a resistive heat and induction heat.

19. The method of claim 17 wherein the electromagnetic heat is from a source selected from the group consisting of resistive AC/low frequency, induction heat, radiofrequency radiation heat and microwave radiation heat.

20. The method of claim 11 wherein the electromagnetic heat is applied with at least one viscosity reducing agent.

21. A method for reducing water usage in a steam-based thermal hydrocarbon recovery technique, the method comprising the steps of:

- a. drilling a first well into a reservoir containing a hydrocarbon;
- b. injecting steam through the first well into the reservoir under a pressure higher than reservoir pressure, dilating the reservoir and increasing permeability;
- c. allowing the steam to heat a first portion of the hydrocarbon;
- d. producing the first portion of the hydrocarbon to surface through the first well;
- e. applying electromagnetic heat to the reservoir to heat a second portion of the hydrocarbon; and

f. producing the second portion of the hydrocarbon to surface.

22. The method of claim **21** further comprising repeating steps b-d at least once before applying the electromagnetic heat.

23. The method of claim **21** further comprising repeating steps b-e at least once after applying the electromagnetic heat.

24. The method of claim **21** wherein the electromagnetic heat is applied by a tool situate in the first well adjacent the reservoir.

25. The method of claim **21** further comprising the step of drilling a second well into the reservoir, wherein the electromagnetic heat is applied by a tool situate in the second well and at least a part of the second portion of the hydrocarbon is produced to surface through the second well.

26. The method of claim **21** wherein the electromagnetic heat is liner/casing conveyed.

27. The method of claim **21** wherein the electromagnetic heat is reservoir conveyed.

28. The method of claim **26** wherein the electromagnetic heat is from a source selected from the group consisting of a resistive heat and induction heat.

29. The method of claim **27** wherein the electromagnetic heat is from a source selected from the group consisting of resistive AC/low frequency, induction heat, radiofrequency radiation heat and microwave radiation heat.

30. The method of claim **21** wherein the electromagnetic heat is applied with at least one viscosity reducing agent.

31. A method for reducing electricity usage in an electromagnetic heat thermal hydrocarbon recovery technique, the method comprising the steps of:

- a. drilling a first well into a reservoir containing a hydrocarbon;
- b. injecting a heated fluid through the first well into the reservoir under a pressure higher than reservoir pressure, dilating the reservoir and increasing permeability;
- c. allowing the heated fluid to heat a first portion of the hydrocarbon;
- d. producing the first portion of the hydrocarbon to surface through the first well;
- e. applying electromagnetic heat to the reservoir to heat a second portion of the hydrocarbon; and
- f. producing the second portion of the hydrocarbon to surface.

32. The method of claim **31** further comprising repeating steps b-d at least once before applying the electromagnetic heat.

33. The method of claim **31** further comprising repeating steps b-e at least once after applying the electromagnetic heat.

34. The method of claim **31** wherein the electromagnetic heat is applied by a tool situate in the first well adjacent the reservoir.

35. The method of claim **31** further comprising the step of drilling a second well into the reservoir, wherein the electromagnetic heat is applied by a tool situate in the second well and at least a part of the second portion of the hydrocarbon is produced to surface through the second well.

36. The method of claim **31** wherein the electromagnetic heat is liner/casing conveyed.

37. The method of claim **31** wherein the electromagnetic heat is reservoir conveyed.

38. The method of claim **36** wherein the electromagnetic heat is from a source selected from the group consisting of a resistive heat and induction heat.

39. The method of claim **37** wherein the electromagnetic heat is from a source selected from the group consisting of resistive AC/low frequency, induction heat, radiofrequency radiation heat and microwave radiation heat.

40. The method of claim **31** wherein the electromagnetic heat is applied with at least one viscosity reducing agent.

41. A method for increasing production of hydrocarbon in an electromagnetic heat thermal recovery technique, the method comprising the steps of:

- a. drilling a first well into a reservoir containing the hydrocarbon;
- b. injecting a heated fluid through the first well into the reservoir under a pressure higher than reservoir pressure, dilating the reservoir and increasing permeability;
- c. allowing the heated fluid to heat a first portion of the hydrocarbon;
- d. producing the first portion of the hydrocarbon to surface through the first well;
- e. applying electromagnetic heat to the reservoir to heat a second portion of the hydrocarbon; and
- f. producing the second portion of the hydrocarbon to surface.

42. The method of claim **41** further comprising repeating steps b-d at least once before applying the electromagnetic heat.

43. The method of claim **41** further comprising repeating steps b-e at least once after applying the electromagnetic heat.

44. The method of claim **41** wherein the electromagnetic heat is applied by a tool situate in the first well adjacent the reservoir.

45. The method of claim **41** further comprising the step of drilling a second well into the reservoir, wherein the electromagnetic heat is applied by a tool situate in the second well and at least a part of the second portion of the hydrocarbon is produced to surface through the second well.

46. The method of claim **41** wherein the electromagnetic heat is liner/casing conveyed.

47. The method of claim **41** wherein the electromagnetic heat is reservoir conveyed.

48. The method of claim **46** wherein the electromagnetic heat is from a source selected from the group consisting of a resistive heat and induction heat.

49. The method of claim **47** wherein the electromagnetic heat is from a source selected from the group consisting of resistive AC/low frequency, induction heat, radiofrequency radiation heat and microwave radiation heat.

50. The method of claim **41** wherein the electromagnetic heat is applied with at least one viscosity reducing agent.

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