DC HIGH VOLTAGE SUPPLY

AC HEATER VOLTAGE SUPPLY

FIG. 6

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This invention relates generally to the recovery of petroleum products from subsurface reservoirs and, more particularly, to the use of high-frequency energy to enhance the recovery of said products, especially with reference to depleted or partially depleted wells.

The recovery of oil or other petroleum products from subsurface reservoirs is conventionally accomplished by sinking wells to oil-bearing strata and allowing the natural pressures within the oil-productive formation to force the fluid into the well bore where it can be conveniently collected. In some oil reservoirs and partially depleted reservoirs there may not be sufficient natural pressure available to force the oil into the well bore at a sufficient rate to be economically profitable.

When such methods can no longer be used to effect an economical rate of recovery, secondary recovery methods, such as injecting water, gas, air, or a combination of these materials into the formation to increase the pressure, are often used. Other methods which have been utilized include the application of heat energy to the formation by either chemical or electrical means or by the direct firing of the oil or gas-bearing regions. The effect of these heating processes is to reduce the viscosity of the fluid and, thereby, increase the rate of fluid flow in accordance with Darcy's law reproduced below:

\[
\frac{dQ}{dT} = \frac{K A dP}{\mu dL}
\]

wherein

\[
\frac{dQ}{dT}
\]

is the rate of fluid flow, \(A\) is the average cross-sectional area of the permeable formation, \(K\) is the permeability of the formation, \(dP\) is the differential pressure causing the fluid to flow through the differential difference \(dL\), and \(\mu\) is the viscosity of the fluid.

Direct firing methods have been found to produce contamination of the crude petroleum or gases that are present. Chemical heating methods have generally been unable to provide a sufficient amount of heat for satisfactory results. Electrical resistance heating methods have proved unsuitable in that the transfer of heat to the oil-bearing strata is primarily accomplished by conduction through the oil on oil bearing strata itself. The rate of heat conduction is quite low and, since the oil is being continuously raised to the surface, a great deal of the applied heat is continuously carried away from the oil-bearing formation and is, thus, prevented from penetrating into the strata.

The invention described herein comprises a system for applying microwave energy to subsurface petroleum formations wherein the R-F microwave energy source is positioned within the well bore at the general vicinity of the oil-producing reservoir. The construction of the invention provides a very efficient heating system which is arranged to utilize substantially all of the available energy in two ways. First of all, microwave energy from the R-F generator source is caused to penetrate directly into the oil-bearing formation without being absorbed to any degree by the crude petroleum oil or gases present in the well bore and in the surrounding reservoir. This penetrating microwave energy heats the oil-bearing form-
open hole-type utilizing a well bore 11 having a steel well casing or liner 12 extending from the surface of the earth to an oil-bearing formation 13. A pump tubing or producing string 14 is concentrically contained within casing 12 and extends downward to the upper region of openhole petroleum reservoir 16. The upper end of pump tubing 14 extends to the well head 15 positioned at the surface of the earth. The upper section of the well bore near the well head shown in FIG. 1A is shown slightly enlarged with respect to the lower section shown in FIG. 1B so that well head 15 may be more clearly described in later paragraphs.

A microwave heating capsule 18, which constitutes one embodiment of the invention, is secured to the lower end of pump tubing 14. Microwave heating capsule 18 contains microwave generating equipment, a heat exchange system, and associated electrical cabling and mechanical support means, all of which are described in more detail with reference to Figs. 2–4. A ground based power supply 19 is positioned near well head 15. Power supply 19 delivers high voltage rectified current and A.C. heater voltage for the microwave generating equipment as well as auxiliary voltages for operating associated electrical and mechanical equipment that may be utilized in capsule 18. These voltages are connected from power supply 19 to the equipment in the capsule by high voltage D.C. cable 20 and low voltage A.C. cable 21 which extend downward through well bore 11. Cables 20 and 21 may be secured to pump tubing 14 by clamps 22 suitably spaced along the length of the well bore.

Oil-producing formation 13, which may vary in thickness over relatively wide limits, is generally composed of a porous core material, such as limestone or sandstone, permeated with crude petroleum in a liquid or gaseous state. The liquid petroleum is brought to the surface through tubing 14 by a conventional pumping system including a pump 67 connected to the sucker rod 20 in order to prevent lateral movement of the casing 12. A plurality of dogs 30 are positioned in housing 29 and enclose pump tubing 14, as is well known in the art. In order to prevent lateral movement of pump tubing 14 and capsule 18 within well bore 11, conventional centralizers 23 are placed at suitable points along the well bore. In order to prevent longitudinal motion in the pump tubing and capsule, an anchor assembly 24 is positioned at a suitable distance above capsule 18. Anchor assembly 24 utilizes a plurality of moveable dogs positioned around the circumference of anchor housing 66. When the pump tubing and capsule assembly have been lowered to their correct positions with respect to the oil-bearing formation 13, the tubing and capsule assembly are rotated within the well bore. This rotation causes cam surfaces (not shown) within the anchor housing 66 to move dogs 25 outwardly so that teeth located on the outer surfaces of the dogs engage and grip the inner walls of well casing 12 to hold the tubing and capsule firmly in place in the well bore. Such a construction is generally well-known to those in the art.

In order to facilitate assembly of the anchor section to pump tubing 14 and to prevent damage to cables 20 and 21 during assembly, a pair of flange connections 26 are used at each end of anchor assembly 24. High voltage cable 20 enters anchor housing 66 through an angularly bored hole 27 in the upper conic section of the housing and passes through the center tubing of the housing and out the other end through a second angularly bored hole 28 in the lower conic section of the housing. Low voltage cable 21 passes through openings between dogs 25.

At the upper end of well bore 11, well head assembly 15 is used to deliver to suitable storage containers the crude petroleum products that are being pumped from the petroleum-bearing reservoir to the surface. Well head assembly 15 comprises a housing 29 having a circular aperture at its lower end so that pump tubing 14 may extend therethrough. A plurality of dogs 30 are positioned in housing 29 and enclose pump tubing 14, as is well-known in the art. A pair of pipes 31 opening into housing 29 are used to carry away the petroleum products which rise to the surface from oil-bearing formation 13. To prevent the gases from escaping out the top of well head assembly 15, packing material 32 is placed around pump tubing 14 above dogs 30. Packing material 32 is held in place by a brass cover 33, the packing material and cover assembly being compressed by a well head cap 34 which is threaded tightly onto housing 29. Suitable openings are drilled through cover 33. Packing material 32, dogs 30 and housing 29 to allow cables 20 and 21 and pump tubing 14 to extend downward through well head assembly 15 into well bore 11.

FIG. 2 shows the exterior of microwave heating capsule 18 which is connected to the lower portion of producing string 14 by flange connection 35. The upper portion of capsule 18 comprises a stainless steel tube 36 having the same diameter as pump tubing 14 and having perforations 37 drilled therein for allowing the petroleum products to enter pump tubing 14 as explained in more detail later. Upper cylinder 36 has heat exchange coils, shown in FIG. 5, positioned therein. Cables 20 and 21 are shown running along the length of upper cylinder 36. Section 88 of the lower portion of capsule 18 is made of stainless steel and has a diameter larger than that of cylinder 36. Section 88 houses a pump for circulating the fluid used in the heat exchange system of the capsule. In the particular embodiment of FIG. 2, there are shown three microwave heating sections 38. These sections contain microwave generating equipment as magnetrons or other devices capable of producing high frequency electromagnetic energy. The portion of the capsule housing the microwave energy generators is made of a suitable plastic material, such as Fiberglas, which allows microwave energy to be passed therethrough without loss to oil-bearing formation 13. Accordingly, by this invention any number of microwave heating sections 38 may be utilized for a particularly desired application. A stainless steel nose cone 39 is secured to the bottom magnetron section to complete the capsule. Descriptions of an exemplary embodiment of one of the magnetron sections of the invention and of the cabling and heat exchange systems of the capsule are given in the following paragraphs with reference to FIGS. 3 and 4.

FIG. 3 shows the interior structure of one microwave generating section 30 of capsule 18. Each of the microwave generating sections utilized in the capsule is fabricated in substantially the same manner as the one shown in FIG. 3. Magnetron sections 38 are housed within the plastic portion of capsule 18 shown in FIG. 3 as plastic shell 69. Each section comprises aluminum structures 70 and 71 which are joined together by a flange connection 72. The upper end of structure 70 also has a flange connector 89 which joins it to the next higher magnetron section positioned directly above. The lower end of structure 71 has a solid flange connector 89 which is used to join it to the next lower magnetron section positioned directly below. Solid flange connector 89 prevents the passage of microwave energy into the succeeding section positioned directly below the section illustrated. Each of the flange connections has a plurality of indentations 73 about its inner surface to allow optical cabling and tubing for the heat exchange system to pass downward along the capsule. The bottommost magnetron section is joined to nose cone 39. A heater transformer 40 having a pair of input terminals (not shown) to which are connected wires 74 and 75 from low voltage A.C. cable 21 is mounted to structure 70 by means of brackets 47 bolted to structure 70 and to transformer 40. A pair of output terminals 76 and 77 mounted at the lower end of heater transformer 40 are connected to cathode heater terminals 41 and 42 by a pair of wires 76 and 79. A cathode insulating
3,179,519

vacuum seal 44 is shown having cooling fins 45 and 91 mounted thereupon. The anode section of the magnetron (not specifically shown) is encompassed by a permanent magnet 49 and has a radiating antenna 50 extending from the lower end thereof inside a dielectric vacuum seal 82. The magnetron is held in place at each end by rubber blocks 51 to prevent unwarranted shock or vibration of the magnetron.

The radiating antenna 50 radiates into a radiation cavity 52 which comprises the lower portion of the inner aluminum structure 71. Radiation cavity 52 has a plurality of longitudinal slots 53 which radiate the microwave energy that is generated out through the plastic shell 69 of capsule 18. In this particular embodiment, slots 53 are substantially symmetrically spaced around the periphery of radiation cavity 52.

The lower portion of structure 71 which forms cavity 52 and has slots 53 therein comprises a resonant structure for producing the required radiating energy. In order to provide a transfer of the radiating energy to the petroleum-bearing formation through the longitudinal arrangement of slots 53 shown here, a plurality of probes 85 are mounted adjacent each slot, as shown most clearly in FIG. 4. Probes 85 project inwardly toward the center of cavity 52. It is desirable that the transfer of energy be as efficient as possible by providing a proper impedance match of the radiating system to the petroleum-bearing formation into which the energy is transferred to the heater of impedance match depends generally on the dimensions of the slot and the make-up of the materials present in the formation. An empirical method of determining the dimensions of the slot may be utilized by radiating energy from the microwave-generation system of the device into a sample of the material that is expected will be encountered in the actual operation of the device and thereby determining the optimum values for the slot dimensions on the basis of experimental measurements of the energy obtained thereby.

High voltage D.C. cable 20 may be connected directly to the cathode of the magnetron or it may be connected, as shown, by a wire 92 to the appropriate transformer terminal 76, and, thence, to the cathode by means of wire 78.

The heat exchange system of the capsule is essentially a series connection of tubes through which a suitable coolant is circulated (shown and described more clearly with reference to FIG. 5). In FIG. 3 the cooled liquid is pumped downward through tubing 56 shown at the left and enters the anode section at the right. The coolant is circulated about the anode and emerges by way of tubing 79 as shown whence it is conveyed downward to the next magnetron section. A return line 57 carries the heated coolant directly from the bottom most magnetron to the heat exchanger located in the upper stainless steel tubing section 36 of the capsule.

The cooling and heat exchange tubing are shown more clearly in the schematic diagram of FIG. 5. In that figure there are shown only four vertically spaced magnetrons 58-61 although any number of magnetrons may be used, depending on the thickness of the oil bearing strata to be heated. The high voltage cable 20 is arranged to have a plurality of ungrounded high voltage leads contained therein, the required ground being obtained from the metallic structure of the pumping tubing and capsule. The magnetrons are arranged in this particular embodiment so that each successive pair of magnetrons is supplied in parallel from one of the plurality of high voltage leads within cable 20. For example, magnetrons 58 and 59 are supplied from high voltage lead 62 and magnetrons 60 and 61 are supplied in parallel from high voltage lead 63. Cable 21 is used to supply excitation voltage for the A.C. heater transformers 40. In the embodiment shown, all of the heater transformers associated with the magnetrons are supplied in parallel with voltage from the single two-wire A.C. cable 21.

The heat exchange system utilizes a series connection of tubing wherein the cooled fluid is carried down tubing 56 into the anode section of the first magnetrons and, thence, to the anode section of the next magnetron, and so on. Return tubing 57 then carries the heated fluid back to the heat exchange coils 64 located in perforated cylinder 36 of capsule 18. A suitable pumping mechanism 65 is used to pump the cooling fluid throughout the closed cooling system. The coolant used may be water or other fluid suitable for such a purpose. A suitable seal 99 is shown between the heat exchange section and the magnetrons.

FIG. 6 shows a more detailed schematic diagram of the wiring of FIG. 5. For clarity only three magnetrons are shown and it is clear that the wiring scheme may be extended to include a greater number of magnetrons if desired. In the figure, power supply 19 has a D.C. high voltage supply 95 and an A.C. heater voltage supply 96 located at the earth's surface. Cable 20 carries a plurality of high voltage leads, such as leads 62 and 63 having a negative voltage thereon, the positive side of supply 95 being grounded. Lead 62 has a first wire 97 connected to the cathode of magnetron 58 and a second wire 98 connected to magnetron 59. A.C. cable 21 is connected in parallel from supply 96 to the primaries of transformers 40, the secondaries of which are connected to the plurality of high voltage leads to provide good electrical insulation. For this purpose, a substantially pure nitrogen atmosphere is used within the capsule and is inserted through plug 100 as shown in the drawings. As can be seen with reference to FIGS. 1-4, application of the operating voltages to the magnetrons causes microwave energy to be radiated from the vertically spaced radiating cavities 52 associated with each magnetron into oil-bearing formation 13. By "microwave energy" is meant energy having a frequency within a range of from about 1000 megacycles to 300,000 megacycles. In one particular embodiment of the invention, it has been found that a suitable frequency of approximately 8000 megacycles may be used. The petroleum products which are present in the well bore and which permeate the formation absorb very little of the microwave energy which penetrates the formation, substantially all of the energy being absorbed by the core material. The temperature rise within the formation causes a drop in the viscosity of the petroleum products and, hence, increases their rate of flow from the formation into the producing string as they enter through perforations 37 at the upper portion 36 of capsule 18.

The petroleum is further heated by heat exchange coils 64 over which it passes and a further decrease in viscosity of the petroleum occurs. This additional decrease in viscosity, due to the application of thermal energy to the crude petroleum, provides a further increase in its rate of flow. It can be seen that the system of the invention utilizes both the microwave energy and thermal energy generated by the magnetrons to increase the rate of flow of crude petroleum products to the surface. It is obvious that the rate of fluid flow may be controlled by controlling the magnitude of the applied microwave energy and the times at which the microwave generators are actuated. It is also clear that the microwave heating device of the invention may be utilized in a closed-hole oil-well structure. In that application, the opening in the oil-bearing formation 13 may be lined with a strong perforated plastic liner which is transparent to microwave energy. Alternatively, the hole may be lined with a stainless steel liner having suitably placed radiation slots or
openings made therein for passage of the energy into the oil-bearing formation.

The particular embodiment shown and described with reference to FIGS. 1-5 does not represent the only embodiment of the invention. Modifications will occur to those skilled in the art within the scope of the invention. Hence, the invention is not to be construed to the particular embodiment disclosed herein except as defined by the appended claims.

What is claimed is:

1. An apparatus for heating a petroleum-bearing formation and adapted to be connected to the lower extremity of a producing string at a position opposite said formation, said apparatus comprising a capsule having first and second portions, said first portion of said capsule containing a plurality of electrical devices mounted therein for simultaneously generating microwave energy and thermal energy, means for supplying excitation voltages to said devices, means for directing said microwave energy at a frequency of between 1000 and 300,000 megacycles into said petroleum-bearing formation, said second portion of said capsule having perforations therein for allowing petroleum products to enter said producing string, means for connecting said capsule to said producing string, said second capsule portion including a heat exchanger positioned therein, means for carrying said thermal energy from said microwave generating devices to said heat exchanger for heating said petroleum products entering said producing string through said perforated portion of said capsule.

2. An apparatus for heating a petroleum-bearing formation and adapted to be connected to the lower extremity of a producing string at a position opposite said formation, said apparatus comprising a capsule having first and second portions, said first portion of said capsule containing a plurality of electrical devices mounted therein for simultaneously generating microwave energy and thermal energy, means for supplying excitation voltages to said devices, resonant cavity means for directing said microwave energy into said petroleum-bearing formation, said second portion of said capsule having perforations therein for allowing petroleum products to enter said producing string, means for connecting said capsule to said producing string, said second capsule portion including a heat exchanger positioned therein, means for carrying said thermal energy from said microwave generating devices to said heat exchanger for heating said petroleum products entering said producing string through said perforated portion of said capsule.

3. An apparatus for heating a petroleum-bearing formation and adapted to be connected to the lower extremity of a producing string at a position opposite said formation, said apparatus comprising a capsule having first and second portions, said first portion of said capsule containing a plurality of electrical devices mounted therein for simultaneously generating microwave energy and thermal energy, means for supplying excitation voltages to said devices, a resonant cavity having a plurality of slots, means for directing said microwave energy into said resonant cavity, whereby said microwave energy is directed outward through said slots into said petroleum-bearing formation, said second portion of said capsule having perforations therein for allowing petroleum products to enter said producing string, means for connecting said capsule to said producing string, said second capsule portion including a heat exchanger positioned therein, means for carrying said thermal energy from said microwave generating devices to said heat exchanger for heating said petroleum products entering said producing string through said perforated portion of said capsule.

4. An apparatus for heating a petroleum-bearing formation and adapted to be connected to the lower extremity of a producing string at a position opposite said formation, said apparatus comprising a capsule having first and second portions, said first portion of said capsule contain-
producing string, said second capsule portion including a heat exchanger positioned therein, means for carrying thermal energy from said magnetrons to said heat exchanger for heating said petroleum products entering said producing string through said perforated portion of said capsule.

8. An apparatus for heating a petroleum-bearing formation and adapted to be connected to the lower extremity of a producing string at a position opposite said formation, said apparatus comprising a capsule having a first plastic portion and a second metallic portion, said first plastic portion of said capsule containing a plurality of magnetrons mounted therein in a vertically spaced relationship for simultaneously generating microwave energy and thermal energy, structure means for providing a plurality of radiation cavities, said structure means having a plurality of vertical slots for directing said microwave energy into said petroleum-bearing formation, said second metallic portion of said capsule having perforations therein for allowing petroleum products to enter said producing string, means for connecting said capsule to said producing string, said second capsule portion including a heat exchanger positioned therein, means for carrying thermal energy from said magnetrons to said heat exchanger for heating said petroleum products entering said producing string through said perforated portion of said capsule.

9. An apparatus for heating a petroleum-bearing formation and adapted to be connected to the lower extremity of a producing string at a position opposite said formation, said apparatus comprising a capsule having a first plastic portion and a second metallic portion, said first plastic portion of said capsule containing a plurality of magnetrons mounted therein in a vertically spaced relationship for simultaneously generating microwave energy and thermal energy, means for directing said microwave energy into said petroleum-bearing formation, said second metallic portion of said capsule having perforations therein for allowing petroleum products to enter said producing string, means for connecting said capsule to said producing string, said second capsule portion including a heat exchanger positioned therein, series connected tubing means surrounding the anode portions of said magnetrons and connected to said heat exchanger, means for circulating a coolant through said tubing means whereby thermal energy is carried from said microwave generating devices to said heat exchanger for heating said petroleum products entering said producing string through said perforated portion of said capsule.

10. An apparatus for heating a petroleum-bearing formation and adapted to be connected to the lower extremity of a producing string at a position opposite said formation, said apparatus comprising a capsule having a first plastic portion and a second metallic portion, said first portion of said capsule containing a plurality of microwave generating devices mounted therein for simultaneously generating microwave energy and thermal energy, a power supply for producing high potential and low potential operating voltages for said devices, a first cable connected from said power supply to said devices for transmitting said high potential operating voltages, said first cable having a plurality of high potential leads connected to a plurality of pairs of parallel connected devices, a single common ground connection associated with said high potential leads, a second cable connected from said power supply to said devices for transmitting said low potential operating voltages, said devices being connected in parallel to said low potential cable, means for directing said microwave energy into said petroleum-bearing formation, said second portion of said capsule having perforations therein for allowing petroleum products to enter said producing string, means for connecting said capsule to said producing string, said second capsule portion including a heat exchanger positioned therein, means for carrying thermal energy from said microwave generating devices to said heat exchanger for heating said petroleum products entering said producing string through said perforated portion of said capsule.

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