

OIL RECOVERY METHOD

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This invention relates to an improved method for recovering petroleum from an underground formation by driving a heat wave through the formation.

It has been found that large quantities of petroleum can be recovered from reservoirs after primary, and in some instances secondary, production methods have been completed by driving a heat wave through the partially depleted reservoir. This is ordinarily accomplished by heating the oil-bearing formation surrounding an injection well to a temperature in the range between 800 and 1200° F., followed by injecting a driving fluid which transfers the heat through the formation toward the producing well. As the heat wave moves through the formation, the oil is heated and displaced from the pores by the driving fluid. With water as the driving fluid in a formation of average rock porosity, i.e., about 20 percent, the heated zone moves through the formation at a velocity roughly half that of the water. As a result of this difference in velocities, part of the oil is displaced from the pores by the water drive in advance of a heat wave. Residual oil is subsequently contacted by the bank of hot driving fluid which displaces part of the oil not recoverable by the cold fluid.

I have found that greater oil recovery may be realized if a fluid, e.g., a gas or a low-boiling liquid, soluble in the oil at reservoir conditions is injected before the heat wave is moved through the formation. This material dissolves in the oil and thereby alters the phase behavior of the oil at the elevated temperature associated with the heat wave. In this manner, crude oil which contained substantially no low-boiling components can be caused to produce a vapor phase when subjected to the conditions of temperature and pressure in the heat wave. This produces an internal gas drive which displaces a greater portion of the oil from the pores of the formation than would be possible with the heat wave alone.

In practicing my invention, the oil-bearing formation is first provided with one or more injection and producing wells. Either a line drive or a radial drive with patterns such as the five-spot may be used in this recovery process. After the well pattern has been selected and the individual wells equipped for their designated service in the operation, steps may be taken to establish a heat wave in the formation.

Although there are several methods which may be used to produce the heat wave, I prefer to burn a portion of the oil in the formation surrounding the input well to establish the heat wave.

A suitable method of heating the formation to initiate combustion of the oil is described in U.S. Patent 2,997,105, Campion et al., issued August 22, 1961. When the face of the formation has been heated to about 600° F., an oxidizing gas is injected to burn the oil in the formation. Combustion of the oil is continued by injecting air or oxygen-enriched air until sufficient oil has been oxidized to establish a heat bank of the desired magnitude. The rate of attenuation of the heat wave is influenced by the thermal conductivity of the formation, well pattern, operating pressure and vaporization properties of formation fluids. A greater amount of thermal energy must be provided in the heat wave for distant well spacings than is necessary for close spacings. In view of this, optimum conditions for different reservoirs will vary.

An air injection rate between 10 and 50 standard

cubic feet per hour per square foot of burning face is satisfactory for reservoirs having a porosity in the range between 15 and 30 percent. At these conditions the burning zone moves through the formation at a rate between 0.5 and 3.0 feet per day, the exact velocity depending upon air injection rate and formation porosity. The hot gases and liquids moving in advance of the heat wave vaporize the volatile components of the formation fluids and displace them in advance of the burning zone. Only the higher boiling components of the crude oil remain and are consumed in establishing the heat wave. The volatilized components flow in the vapor phase until they reach a zone where the composition and temperature of the formation fluids enable them to condense or become absorbed.

The oil-soluble fluid may be injected either before the heat wave is established or before the injection of a driving fluid; however, I prefer the latter. When it is present during the time the heat wave is being established, there is a tendency for it to be smeared through a wide and sometimes irregular band in the formation as the combustion products move toward the producing well. On the other hand, the oil-soluble fluid is subjected to thermal degradation when it is injected after the heat wave is established and driven through the high temperature zone.

Suitable oil-soluble materials which may be injected to increase the amount of crude oil recovered are the paraffin-series hydrocarbons containing less than about eight carbon atoms per molecule. In general, I may use any of the paraffin hydrocarbons, either alone or mixtures thereof, which will dissolve in the crude oil in advance of the heat wave then vaporize at temperatures and pressures prevailing in the heat wave. Natural gas is a suitable material when a high partial pressure of the injected fluid is desired. When a somewhat lower partial pressure is required, hydrocarbons having from three to seven carbon atoms per molecule may be used. Natural gasoline is a convenient source of these hydrocarbons. The isomeric and olefinic hydrocarbons having suitable physical properties may be used; however, they are seldom available on a basis competitive with the normal paraffin hydrocarbons.

A quantity of the oil-soluble material should be injected which combines with the trapped oil to produce a vapor volume in the heat wave equivalent to the trapped oil volume, i.e., the residual oil saturation contacted by the heat wave. If, for example, oil is to be recovered by displacing a heat wave through the formation with water, the water flood moving at a velocity approximately twice that of the heat wave may displace part of the oil leaving a lower percent oil saturation. Approximately the same proportion of the pore space will be occupied by gas after passage of the heat wave as was occupied by the trapped oil ahead of the heat wave. When the reservoir oil contains substantially no components which will be vaporized in the heat wave, it is necessary to inject a quantity of the volatile liquid equal to the residual oil saturation. In those formations containing oils having some volatile components, theoretical recoveries approaching 100 percent are possible by injecting only sufficient volatile material to combine with the volatile components of the oil and displace the residual liquids. Maximum recovery will be obtained when there is sufficient volatile material to replace the residual oil saturation.

A satisfactory solution of the low-boiling material in oil is one which has a phase relationship exhibiting approximately equal volumes of vapor and liquid at the temperature and pressure existing in the heat wave. In some formations it may be desirable to have a vapor-liquid volume ratio as great as 2:1. To obtain the desired composition it is necessary to select a low-boiling fluid which dissolves in the oil in sufficient concentration

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at formation temperature and pressure to produce the desired phase relationship at the temperature and pressure in the heat wave.

The swelling or increase in oil volume which occurs with vaporization displaces the oil from the individual traps into the path of the driving fluid. Oil is displaced most efficiently from traps which are open at the bottom. Oil in traps having more complex geometry is more difficult to displace and comparable recovery efficiencies require the higher vapor-liquid ratios for the enriched crude oil.

Several factors influence the selection of the oil-soluble material. High water injection pressures are necessary in formations having a low permeability to the bank of oil, water and gas which accumulates at the leading edge of the heat wave. Where this condition is found, high vapor pressure material such as methane must be used to obtain a satisfactory phase relationship at the high driving pressure. High vapor pressure materials are also necessary in reservoirs where there may be a substantial decrease in the temperature of the heat wave before it reaches the production well. Such temperature decreases may result when operations are carried out over an extended period of time or when the adjacent formations have high rates of heat transfer.

It is preferable to use oil-soluble fluids which do not vaporize readily because a greater quantity of those materials can be dissolved in the crude oil at low pressure. The paraffin hydrocarbons having from three to about seven carbon atoms per molecule are particularly suitable in formations which do not require injection pressures greater than about 300 to 400 pounds per square inch and which do not have high rates of heat loss.

The oil-soluble fluid is displaced into the formation and through the heat wave by a driving fluid such as water or gas. After passage through the high temperature zone where complete vaporization occurs, the vapors move forward until they reach a zone where the temperature, pressure, and liquid composition enable them to condense and dissolve in the crude oil. In this manner the low-boiling materials are transferred in advance of the heat wave to the relatively non-volatile crude oil. When the heat wave subsequently reaches the oil containing the low-boiling component, vaporization occurs and displaces the trapped oil from the pores. The low-boiling material is redissolved when it reaches cool oil, thereby constituting a cyclic process.

Injection of the driving fluid is begun following injection of the volatile, oil-soluble material. The rate of injection should be below that which produces fracturing of the formation or damage to well equipment. Induced fractures in the formation are undesirable because they frequently enable the injected fluid to bypass part of the formation. Also, the injection pressure should not exceed that which permits vaporization of the injected fluid at the temperature of the heat wave. The first fluid which is injected extracts heat from that portion of the formation nearest the well. In this manner the heat in the formation is progressively transferred from the heated zone nearest the injection well to the cooler zone in advance of the heated zone. The oil-soluble material which was injected earlier is vaporized at the elevated temperature. As the gas phase develops, fluids are displaced from their pores into the bank of fluids moving toward the producing well. The expansion of the injected fluid to produce a vapor phase in the pores at the prevailing temperature and pressure results in higher total recoveries than are possible by a hot water drive alone.

A quantitative demonstration of the effect of partial vaporization of trapped oil on total recovery was made

in the laboratory. A sandstone core having a residual oil saturation of 28 percent of the pore space was water-flooded with 10 pore volumes of water at temperatures up to 300° F. and at 150 p.s.i.g. No oil was swept from the core at these conditions. Oil displacement started when the temperature was raised to 350° F. This resulted in recovery of 80 percent of the residual oil. The composition of the oil used in these tests was such that vaporization at this pressure did not begin at temperatures below 330° F.

Although the most significant increases in total recovery are realized with crude oils which do not vaporize partially at the temperature and pressure prevailing in the heat wave, it should be understood that this method will also enhance recovery in those formations where partial vaporization occurs.

I claim:

1. The method of recovering oil from an underground formation having an injection well and a production well comprising establishing a heat wave in said formation near said injection well, injecting at said injection well a quantity of an oxygen-free, oil-soluble fluid which dissolves in said oil between said heat wave and said production well, immediately thereafter injecting an oxygen-free aqueous driving fluid at said injection well whereby said heat wave is moved toward said production well vaporizing said oil-soluble fluid and producing a two-phase system which displaces said oil toward said producing well, and withdrawing oil from said production well.

2. The method of claim 1 wherein the oil-soluble fluid is a petroleum gas containing principally methane with minor amounts of other paraffin hydrocarbons.

3. The method of claim 1 wherein the oil-soluble fluid is a mixture containing paraffin hydrocarbons having from three to seven carbon atoms per molecule.

4. The method of claim 1 wherein the quantity of said oil-soluble fluid which is injected will dissolve in said oil beyond said heat wave and thereafter produce a two-phase system at the temperature and pressure of said heat wave having a vapor volume substantially equal to the volume of said oil prior to the solution of said oil-soluble fluid therein, whereby said vapor disposes said oil from the pores of said formation.

5. A process for recovering oil from an underground formation having an injection well and a production well comprising the steps of lowering a heater into said injection well and heating the face of said underground formation to a temperature of about 600° F., injecting an oxygen-containing gas and burning oil in said formation adjacent said injection well to establish a heat wave in said formation, stopping injection of said oxygen-containing gas and discontinuing the heating of the face of said formation, injecting into said formation through said injection well a quantity of paraffin hydrocarbons having no more than about seven carbon atoms in the molecule said quantity of paraffin hydrocarbon having a volume at the temperature and pressure of said heat wave approximately equal to the volume of oil in said formation, immediately thereafter injecting an oxygen-free aqueous driving fluid through said injection well to displace said heat wave through said formation and recovering oil at said production well.

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