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# OIL RECOVERY PROCESS

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My invention relates to a process for the recovery of oil and gas from oil-bearing underground reservoirs by thermal means. More particularly, it relates to a stepwise process wherein initially a heat wave is propagated within the formation and finally the heat content of the wave is employed to finish the recovery process by a hot water drive.

In order to recover oil from an underground reservoir by means of wells, energy is required to bring the oil into the well bore from remote portions of the formation. It is well known however that the energy content of the original undisturbed reservoir, as a generality, is insufficient to recover all of the oil. Even in the unusual case of reservoirs containing sufficient gas under pressure to provide the theoretical energy requirements for complete oil removal, a large proportion of the energy is wasted because the gas escapes from the producing wells without bringing oil to the well bore in amounts corresponding to the available energy. Hence primary production rarely if ever results in complete recovery of the oil. Although injection of extraneous water or gas can be used to supplement the natural energy of a reservoir or, in secondary recovery methods, to supply energy in reservoirs which have been depleted in energy, it is common knowledge that these methods, whether applied simultaneously or successively, do not recover all of the oil, probably because of viscosity, capillarity and adsorption effects within the formation.

Thermal means have been often proposed for more efficient oil recovery whereby thermal energy is introduced into the reservoir by means of hot liquids or gases or is generated within the formation by in situ combustion of part of the oil or of other combustibles. In these methods, the heat generated at one point, either in the injection well bore or at the combustion point within the formation, must be moved to other points in the formation. Usually, a gaseous heat carrying medium is employed which transmits the thermal energy to other parts of the formation and at the same time functions as a source of mechanical energy as in the case of a gas drive. Improvement in oil recovery efficiency then may result by reason of the increased temperature of the oil which decreases its viscosity and by cracking and distillation of the oil, but major improvement in recovery is most effective if the temperature is increased high enough, so that it can be moved toward the producing well as a vapor rather than as a liquid.

The present invention is based on findings developed in the course of extensive investigation of thermal recovery both in the laboratory and in the field. Thus I have found that the use of water to utilize the heat generated by an initial combustion drive provides means for recovery of oil by a thermal process which eliminates disadvantages of previously proposed thermal methods. My process is based in part on the discovery that a heat wave propagated in the formation by in situ combustion caused by injection of a lean mixture of oxygen-containing gas (fuel content less than lower explosive limit) through an injection well toward a producing well results in a broadening annular band or wave of peak temperature. This is surprising since attenuation of the wave because of its ever increasing radius from the input well would be expected. My invention also applies the discovery that in situ generation of steam results in substantially complete removal of oil from the formation. Thus the oil is made mobile and recoverable at a temperature corresponding to the boiling point of water at the subsurface pressure (considering capillary effects, 200° F. to 1000° F.) prevailing so that temperatures in the cracking range can be avoided in the presence of steam.

In the practice of the invention, a high temperature heat wave is established within the formation. Advantageously, the heat wave is established by burning a fuel-air mixture in the bore of an input well at formation level. The fuel-air mixture is proportioned to provide a temperature within the range of about 1000° to 2000° F. A sufficient period of preheating is provided to heat a substantial portion of the rock formation surrounding the well bore to a temperature above the ignition temperature for hydrocarbons in the formation, i. e. above about 450° to 500° F. After the oil-bearing strata around the well bore for a radius of several feet has been heated to high temperature, preferably above 1000° F., combustion in the well bore is terminated. The heated zone is now moved into the formation by injecting unheated, non-combustible gas such as air or air containing an amount of fuel gas below the explosive limit. Alternatively, air and fuel gas may be injected alternately in a manner preventing burning within the well bore. Alternatively fuel gas containing an oxygen content below the rich explosive limit may be used for movement of the heated zone into the formation. The gases enter the well bore cold and pick up preheat from the rock face. By transfer of heat outwardly through the rock the heated zone is moved away from the well bore. Once the well bore has been cooled below the ignition point a heat wave in the sense of the invention has been established which can be propagated within the formation. An oxygen-containing gas drive is employed to propagate the heat wave, advantageously air at as high an input rate as practicable taking into account the permeability of the rock, power requirements for compression and pressure limitations. The input rate and partial pressure of oxygen are maintained in any event high enough to insure combustion of hydrocarbon residues in the rock as the oil is released and moved out into the formation before the advancing heat wave. If the residue is too lean to provide sufficient heat to maintain the peak temperature of the advancing wave at a high level, e. g. about 1000° F., fuel gas in a proportion below lean explosive limits may be injected with the injected air. The injected gas progresses radially out into the formation from the input well and is preheated to above the ignition temperature as it passes through the peak temperature zone. As the preheated air comes into contact with residual fuel at the leading edge of the wave, the in situ combustion process is continued, generating additional heat and thus propagating the heat wave in the form of an advancing annular ring.

The total heat content of the wave is increased by providing a high partial pressure of oxygen. It is most practical to use air, or a lower concentration of oxygen than contained in air. Under these conditions, I have found that the breadth of the wave continuously increases as the wave advances through the formation. In the process of my invention, therefore, water can be injected with the gas to increase the heat carrying capacity of

the injection medium, thus further accelerating the movement of heat through the improvement in heat transfer capacity, without loss of combustion. For example, a mixture comprising 12 cubic feet of air or 12 cubic feet of a perfectly combustible air-gas mixture per pound of water may be employed. The object is to furnish the maximum sensible heat consistent with maintenance of a peak temperature above the ignition point for residual hydrocarbons within the formation.

Although the entire recovery process can be conducted by thermal means by proceeding in this manner until the heat wave reaches the producing well or wells, it is an essential feature of my invention to switch from the in situ combustion step to in situ steam drive by replacing air injection with water injection. The change is made once the heat content stored in the rock is sufficient to carry the heat wave without further combustion by means of water drive to the producing well or wells at a temperature equivalent to the boiling point of water under the pressure conditions prevailing at the producing well or wells. Operating in this manner, maximum utilization of heat is obtained without sacrifice in recovery efficiency. Combustion is continued only long enough to provide for release of the optimum quantity of heat and in situ steam generation has been found to effect substantially complete release of recoverable oil from the formation. Since a much lower temperature is used, that is a temperature corresponding to the boiling point of water under the pressure prevailing at the producing well, instead of the combustion temperature, less cracking of the oil occurs. The result is improvement in liquid recovery and in quality of the liquid product.

The invention may be illustrated by way of an example of a field operation designed to accomplish tertiary recovery of oil from the Bartlesville formation in the Nowata-Delaware area of Oklahoma. Representative average data for the formation follow: Thickness 30', porosity 20%, average permeability 150 millidarcys, oil saturation 35%, water saturation 35%, gas saturation 30%, true density of rock 160 pounds per cubic foot.

A five-spot pattern in which the number of input wells is equal to the number of producing wells is used although the description is confined to one element of the five-spot pattern. The well spacing employed is 330 feet between like wells, or

$$330' \cdot \frac{\sqrt{2}}{2} = 234'$$

from input well to producing well. In conducting the operation according to the example, the following additional basic data are applied or are assumed.

Temperatures: Initial formation temperature 70° F. (as found in the Bartlesville sand at Nowata); peak temperature of the wave 1000° F. (from petrographic examination of cores from field trials, corroborated by laboratory tests); final temperature of steam drive 300° F.

Heat capacities: Gas 0.02 B. t. u./°F./s. c. f.; rock 0.2 B. t. u/°F/lb.; water 1500 B. t. u./lb. between 70° F. and 1000° F., and 1200 B. t. u./lb. between 70° F. and 580° F. (from standard Mollier diagram).

Residual saturation after steam drive: 6% oil, 85% water, 9% gas.

Heat generated in burning: 500 B. t. u./s. c. f. of oxygen, 20,000 B. t. u./lb. of oil.

Injection rates: 1,000,000 s. c. f./day of air (oxygen content: 20%), oxygen in the produced gas 2% (as determined by field trials). Water injection rate: 200 B./D.

The preliminary operations include installation of a burner of the type described in application Serial No. 97,142, filed June 4, 1949 of John J. Piros and Oliver F. Campbell at formation level. The burner is ignited and hydrocarbon gas is burned with air in the bore of the injection well in a manner injecting the resultant exhaust gases into the formation. The well burning operation is continued until the oil bearing strata have been heated for a radius of several feet around the well bore to a temperature of the order of 1500° F. Combustion in the well bore then is stopped by switching to injection of unheated air or field gas.

In practicing my invention the high temperature front is advantageously established within the formation by burning fuel, conveniently natural gas or crude oil, with air at high temperature either on the surface, or preferably within the hole. The resulting combustion gases under elevated pressure are forced into the porous oil-bearing stratum for a length of time sufficient to raise the temperature of a large body of sand surrounding the well to a temperature below the fusion temperature of the rock but well above the ignition temperature of the residual carbon. At the same time, the formation is partially re-pressured with resulting flow of cold oil and gas toward the outlet wells. Alternatively, however, other ignition means such as chemical igniters and fuels may be employed, switching to air drive once ignition is accomplished.

During the fuel-burning period, there is normally a large excess of oxygen in the combustion gases because of the use of dilution air in the burner system, which insures clean combustion and prevents the formation of soot that might clog the formation, and additionally assists in heating up the oil bearing rock by burning carbonaceous residue and some oil.

The use of a bottom-hole burner is advantageous because it eliminates the need for expensive alloy casing and expansion joints. However, the combustion gases may be produced by burning at the surface in any desired type of combustion system producing a stream of hot gas under high pressure or a system combining a surface preheater and bottom-hole burner may be used. With bottom-hole combustion, various ignition schemes may be used, for example electric sparking, thermite, or other incendiary bombs. However, a jet-type, spark ignited combustion system with a high velocity, turbulent air and gas flow in which a relatively large volume of diluent air or gas is introduced progressively into the burning zone provides a convenient and reliable bottom-hole system. Recycle gas may be utilized as diluent after the temperature has been built up, and where gas engine driven compressors are employed, the engine exhaust may be utilized as recycle or diluent gas.

The inlet pressures will vary according to the distance between producing and input wells, the thickness and permeability of the oil-bearing stratum, and the oil and water content of the formation. Similarly, the quantity of gas introduced will be affected by the desired pressure, temperature of the input gases, and the conditions and heat capacity of the oil-bearing stratum. The pressure for example will ordinarily exceed 60 p. s. i. g., but because of problems of reservoir control is maintained at a moderate figure and, of course, is ultimately limited by the overburden. To minimize plugging or cementing of the porosity of the formation, after-scrubbers or other filtering devices should be employed on compressors in order to remove iron rust or other troublesome carry-over. Similarly, it is desirable to incorporate similar devices in the liquid knock-out system employed for handling recycle gas.

The gas produced is recovered and after recompression to compensate for pressure drop may be recycled. Maintaining superatmospheric pressure on producing wells markedly reduces power costs for recompression in recycling operations. Depending upon its fuel content, the produced gas may be burned as fuel or utilized as gas recycle. Readily liquefiable or other valuable components may be recovered as by absorption prior to utilization as recycle. Pressure drop is desirably kept low and may be controlled by keeping the volume gas rate low and by operating at a high pressure level.

Analysis of the produced gas, as by the Orsat method,

for oxygen and carbon dioxide content provides a means for determining the state and progress of the front within the formation. It is helpful to observe pressure differentials between inlet and outlet flow, which are affected by the temperature, the permeability, whether fusion is occurring, whether an oil and water block is building up, and the position of the heat transfer point and the revivifying combustion point. Control timing is also assisted by the use of deep-well thermometers or temperature recording devices.

In applying the invention to large scale recovery operation, it is advantageous to utilize a logically spaced pattern of input and outlet wells. In many of the oil fields which have been extensively gas pressured or water flooded, wells have been drilled in 5-spot or 9-spot patterns which will be suitable for applying the invention to further recovery. It may be necessary, however, to drill a new input well or to pull the old casing and replace it with pressure tight piping. The holes may be tightly cemented with a high temperature resistant cement at the top of the formation where necessary to confine the combustion and recycle gases within the formation stratum. If non-uniform permeability is indicated by core analysis or erratic production, the use of well packers can be employed to seal off excessively permeable strata.

In establishing the wave, it is important to regulate the temperature during the period of combustion within the bore of the input well by regulation of the proportions of secondary air in the burner. Advantageously, temperature is maintained in the range of 1000° to 2000° F., preferably about 1500° F. Too low a temperature will delay development of the heated zone because of poor ignition. Too high a temperature will cause sintering and spalling of the sand. Combustion in the porous rock may be initiated with a gas-air mixture in the non-explosive range, e. g. below 4% methane in air; after combustion has been initiated, it is continued by charging in the non-explosive range, e. g. below 4% methane in air. By way of example, a mixture providing a heat release of 30 B. t. u. per cu. foot of air may be employed, but as the temperature builds up to the ignition temperature of hydrocarbons in the formation e. g. 500° F., the fuel content is dropped from the 30 B. t. u. per cu. foot to 10 B. t. u. per cu. foot of air

With proper secondary air control on the burner to give a temperature rise to within the 1000° to 2000° F. range, about 5 to 8 days heating time should be sufficient to establish the heated area at the bottom of the injection well. It is necessary to stop combustion at the well bore so that by cooling the sand face the heated zone may be moved out into the formation. Thus, the wave form or profile is established as the trailing edge appears. During the period of cooling and movement of the hot zone, an unheated gas mixture, which is either non-combustible or which is handled in a manner preventing combustion at the sand face or back, must be employed. For example, using air the fuel content should not exceed 40 B. t. u. per cu. foot of air or a stationary heat front will develop. It is desirable to use air because the excess of oxygen expands the wave more rapidly and contributes a greater amount of stored heat in the heat wave. As illustrated in the above example, the propagation of the wave is continued until sufficient heat is built up in the formation in relation to the volume and porosity of the unheated portion of the formation between the leading face of the wave and the producing wells to keep the water injected in the water drive above the boiling point up to the end of the recovery process, taking into account the pressure and depth of the well. During the propagation step, air alone, air in admixture with recycled field gas and/or fuel gas may be employed as the driving medium. The use of fuel gas may be necessary to maintain the desired peak temperature if the carbonaceous residue left in the sand upon release and movement forward of the bulk of the oil content is insufficient for the purpose. In this case, the proportion of fuel must be regulated below or above the explosive level, or it must be injected in alternate cycles with the air, to prevent burn back from the peak temperature zone and development of a stationary front rather than a moving wave. The use of field gas, recycled under pressure, reduces the compressor load for the gas injection operation. In using air, a small amount of fuel gas, say 1 to 5 B. t. u. per cubic foot is advantageous as a tracer to indicate the position of the trailing face of the heat wave. A window well can be drilled and the presence or absence of carbon dioxide in gas produced from it can be determined by analysis. Reasonably definite location of the leading and trailing faces of the heat wave is important in determining the optimum point in the process for changing from the wave propagating drive to the water drive. For with the width of the heat wave established, its heat content can be calculated by simple computation from available thermal and formation data as illustrated in the above example and then compared with the quantity of heat necessary to provide the desired termination temperature for the hot water drive, usually about 300° to 400° F., but equivalent to the boiling point of water at the pressure prevailing in the producing well.

When straight air is utilized as the wave propagating medium, the leading face of the wave may travel as much as 3 times as fast as the trailing face. Although the heat transfer wave corresponding to the trailing portion and the combustion wave corresponding to the peak temperature portion may be made to coincide by appropriate control of total average oxygen input as described in U. S. Patent No. 2,642,943, it is advantageous to introduce water with the wave propagating medium to accomplish a similar purpose. Because of the much higher heat capacity of water, pound for pound the horsepower requirements for injecting the propagating medium may be markedly reduced by water injection. In the wave propagating step, therefore, injection of water in an amount in the approximate range of 2 to 10 gallons per thousand cubic feet of gas is recommended. The water injected with the gas in the propagating step also improves oil recovery by providing in situ steam generation ahead of the peak temperature portion of the wave. Although the water is vaporized as it passes through the wave, it is condensed subsequently ahead of the wave and provides sufficient liquid water saturation in the formation to promote desorption of the oil from the matrix as the wave approaches and revaporizes it. Thus only the heaviest residual portion of the oil which would be unrecoverable in any event remains behind to serve as fuel in the propagation of the heat wave.

By finishing the process with a water drive providing in situ steam generation to utilize the heat content of the wave, several substantial advantages are obtained. The total quantity of heat required for a complete recovery process may be reduced as much as a half. Similarly, the power requirements for injecting the drive media are tremendously reduced. The time required to attain complete recovery is less. In addition more certain recovery of the oil banked ahead of the heat wave is effected in view of the greater efficiency of water as an oil displacement medium than gas. Also oil consumption by combustion and cracking to gaseous hydrocarbons is avoided in the in situ steam generation phase of the operation.

The effectiveness of oil removal and recovery has been established in field tests on a portion of the Bartlesville formation and has been confirmed by numerous laboratory experiments. Using a single input well with a ring of producing wells in a 34-foot bed of sand, 295 MM cubic feet of air-fuel gas mixture was injected over a period of approximately 10½ months. During the test period, 34.6 MM cubic feet of oxygen were consumed. By oxygen balance, the burned area was calculated to be a circle of about 90 feet to 100 feet in diameter. Two window wells were drilled into the formation,

however, 50 feet and 170 feet respectively from the injection well, and by means of cores and temperature readings taken from the two window wells the actual extent of the burned area was estimated at about 120 feet.

After 10½ months, the leading edge of the heat wave was at 58.7 feet from the injection well with the trailing face at 41.5 feet as determined by a balance of input and output oxygen, assuming that each cubic foot of oxygen burned liberated 500 B. t. u. and that the peak temperature of the sands reached 1400° F. The position of the trailing face was confirmed by temperatures taken in the nearer window well. Heat losses, based upon data calculated from temperatures taken at different levels in drilling the window wells, were indicated as 2% maximum to over- and under-burden and possibly 5% by conduction parallel to the wave. Further figures, based upon daily injection of 1.0 MM cubic feet of air for an additional 300-day period, showed that the front would be 104 feet from the injection well with the rear face at 73.5 feet. The significance of these figures is that the width of the wave is ever widening so that there is a vast quantity of stored heat available for hot water drive at the proper point in the operational sequence. The data also show that the possibility that combustion will be lost during the heat wave propagation step is remote since preheat is always available for re-ignition.

Cores taken from the nearer window well showed that at least 93% of the oil in place had been removed. By balancing actual oil production from the ring of producing wells, oil moved out into the formation beyond the ring of producing wells as obtained by averages of oil-gas ratios at the producing wells, the liquid or residual oil converted to low B. t. u. gas-air mixture and the liquid gas or residual hydrocarbons actually consumed by oxygen and recovered or exited as carbon dioxide, data on hydrocarbon recovery were obtained. Test data available indicated that 90% liquid oil recovery may be expected from the heating period followed by steam drive produced in situ by water injection, from oil sands containing 600 barrels of oil per acre foot, at the start of the combined operation.

I claim:

1. In the recovery of oil from an oil-bearing underground formation by thermal means wherein a heat wave is established within the formation, the steps comprising heating the formation around the bore of an input well to establish a heated zone in the formation thereabout having a temperature above about 500° F., moving the said heated zone out into the formation and cooling the input well bore by injection of a cooling non-combusting gas therein, and thereafter discontinuing the use of the input well bore as a heat source, propagating the heat wave within the formation by injection of an oxygen-containing propagating gas through the input well towards an adjacent output well at an average input rate of oxygen sufficient to maintain a peak temperature in the wave above the ignition point, injecting water into the underground formation from said input well bore after the heat content of the wave during propagation is sufficient to provide a peak temperature in the wave when it reaches the output well equivalent to the boiling point of water at the pressure prevailing in the output well, thereafter discontinuing the injection from the input well of any propagating gas and carrying the heat wave to the output well by further injection of water into the formation from the input well.

2. The process of claim 1 in which the oxygen-containing gas is air.

3. The process of claim 1 in which the oxygen-containing gas is a mixture of air and a combustible fuel.

4. The process of claim 1 in which water in dispersible quantities is injected with the oxygen-containing propagating gas.

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