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WATER FLOODING PROCESS WITH PRE-PRESSURE STEP

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This invention relates to the production of petroleum by secondary recovery methods, and in particular concerns an improved water-flooding process.

Among the various methods presently employed for recovering petroleum from oil-bearing formations which have become depleted to the point where petroleum no longer flows naturally into wells penetrating such formations, the secondary recovery method commonly known as "water-flooding" probably enjoys widest exploitation. In brief, such method consists essentially in pumping water into one or more injection wells under a pressure sufficient to cause the water to flow out through the oil-bearing formation towards one or more other wells which serve as producing wells. Theoretically, as the water flows through the oil-bearing formation the residual oil contained therein is forced ahead of the advancing water front into the producing wells from which it may be pumped to the earth's surface. In many instances, however, this method proves ineffective by reason of the occurrence of strata of high permeability extending between the injection and producing wells. The water chooses the path of least resistance, i.e., the strata of highest permeability, and hence travels from the injection wells to the producing wells in more or less well-defined channels and fails to sweep the residual oil from the formation as a whole. This condition is often aggravated by the fact that the strata of highest permeability are water-bearing or at least water-wet, and their permeabilities are higher with respect to water than to other fluids, particularly petroleum.

For the most part, the various means proposed for alleviating these difficulties have been based on the concept of injecting into the high permeability or "thief" strata a liquid material which is capable of being solidified therein to form a solid water-impermeable plug. However, the solid plugs so formed invariably extend into the strata for only a very short distance, with the result that the aqueous flooding medium soon by-passes the plugs. Moreover, in localities where water-bearing and oil-bearing strata lie so closely adjacent that they cannot be isolated one from the other by packers inserted into the well bore, it is substantially impossible to avoid plugging both types of strata simultaneously, and while the use of selective plugging materials (i.e., plugging materials which are soluble in oil but insoluble in water) has enjoyed some success, the rate at which crude petroleum can dissolve its way through a plug of oil-soluble solid located in a tiny interstice is extremely slow.

It is accordingly an object of the present invention to provide an improved method of recovering petroleum by water-flooding.

Another object is to provide an improved method for plugging subterranean strata throughout a relatively extended portion of their length.

A further object is to provide an improved method for water-flooding formation which comprise strata of widely varying permeabilities.

Other and related objects will be apparent from the following detailed description of the invention, and various advantages not specifically referred to herein will be apparent to those skilled in the art.

I have found that the above objects and attendant advantages can be realized through the use of a viscous hydrocarbon oil as a selective plugging agent. More particularly, I have found that where, in a water-flooding operation, there are encountered strata of widely differing permeabilities, e.g., a formation in which there occur strata whose permeabilities vary by a factor of 20 to 100 or more, a very appreciable improvement in the uniformity of the flooding front can be attained by forcing a suitable aqueous or non-aqueous liquid into the formation from the injection well or wells under an elevated pressure below the formation breakdown pressure, thereafter injecting a viscous hydrocarbon oil into the formation under a considerably lower pressure, and finally forcing a conventional aqueous flooding medium into the formation in accordance with conventional water-flooding procedure. The initial step is carried out in such a manner that upon the completion thereof substantially equilibrium conditions are attained within the formation in the immediate vicinity of the well bore, i.e., in such manner that the pressures within the various strata which comprise the formation are substantially the same in high- and low-permeability strata alike. In the second step, wherein the pressure within the well bore is reduced to a lower value, the pressures within the various strata will decline, but at varying rates depending on the permeability of each stratum. Thus, when the pressure against the formation face is lowered by reducing the pressure on the fluid within the well bore, the rate at which the pressure within any particular stratum declines to the lower value is directly proportional to the permeability of that stratum. Consequently, at any given instant within a short time after the pressure is reduced within the well bore, the pressure within any particular stratum is indirectly proportional to the permeability of that stratum. Thus, the strata of highest permeability will be at lowest pressure and the strata of lowest permeability will be at highest pressure. There is thus created within the formation a plurality of zones of different pressure, the number and location of such zones corresponding to the number and location of the strata which comprises the formation, and the pressure within each zone being indirectly proportional to the permeability of the stratum to which it corresponds. Such condition is of course of only temporary existence since with the passage of time equilibrium pressure conditions within the formation will eventually be attained. However, in accordance with the invention, a viscous oil is forced into the formation while the pattern of pressure zones still exists, and since the back pressure opposing entrance of the viscous oil into a particular stratum is indirectly proportional to the permeability of that stratum, the distance the oil penetrates into the stratum is directly proportional to the permeability. Consequently, the viscous oil penetrates most deeply into the strata of highest permeability and least deeply into the strata of lowest permeability. Upon completion of the second process step, each of the strata which comprise the formation is plugged with a body of viscous oil, the length of which body (and hence the resistance with which it opposes movement through the strata) is proportional to the permeability of the stratum which it occupies. Accordingly, when, in accordance with the third process step, an aqueous flooding medium is introduced into the well bore and is forced outwardly into the formation, it enters the strata of lowest permeability at substantially the same rate as it enters the strata of highest permeability. The flooding medium hence advances through the formation and drives the bodies of injected oil ahead of it in a pattern which more nearly resembles a planar front than that attained in the absence of viscous oil injection.

Apart from the selective plugging effect described above, the process of the invention attains better sweep efficiency by means of a more favorable viscosity rela-

tionship between the connate petroleum and the flooding medium. In any given stratum the efficiency with which the connate petroleum is swept therefrom by a flooding medium is directly proportional to the ratio of the viscosities of the two liquids, i.e., the sweep efficiency is proportional to the value of V_1/V_c, where V_1 is the viscosity of the flooding medium and V_c is the viscosity of the connate petroleum. In the present process, in the high permeability strata the actual flooding front consists of an oil which is much more viscous than a conventional aqueous flooding medium; thus, the value of V_1 (and hence of V_1/V_c) is much higher than in conventional water flooding processes, and the sweep efficiency is likewise higher than that attained in conventional flooding processes.

Considering now the process of the invention in further detail, the initial step consists in introducing a suitable liquid into the bore of an injection well or wells, and applying thereto sufficient pressure to force said liquid out into the various strata which comprise the formation being flooded. In accordance with the conventional practice, the latter is usually isolated from the rest of the bore by menas of suitable packing devices. Since the purpose of this initial injection step is merely one of establishing within the formation a back-pressure which is substantially uniform in the various strata thereof, the identity of the liquid is not important. It should, of course, be inert with respect to the formation and the fluids contained therein, and should have a viscosity which is not substantially greater than that of the connate petroleum. Water and brine are satisfactory for use in formations which do not contain appreciable amounts of hydratable clays (i.e., in formations where water and brine are inert), but it is preferred to employ a hydrocarbon oil, e.g., petroleum distillates, heavy gas condensates, kerosene, topped crude, etc. Local crude oil is particularly preferred because of its immediate availability, suitable viscosity, and inertness. The amount of liquid employed in the initial pre-pressuring step is governed by a number of factors, including the fracturing pressure of the formation, the permeabilities of the various strata which comprise the same, and the viscosity of the liquid itself. However, any appreciable amount will attain some benefit, although it is preferred to employ enough so that it penetrates into the high permeability strata for a distance of at least about 5 feet, and preferably 50 feet or more. The pressure under which the pre-pressuring liquid is forced into the formation must of course exceed the normal formation pressure by a substantial amount but must not exceed the overburden pressure so as to cause fracturing. Preferably, the pressure should approach the overburden pressure as closely as possible without exceeding the same, although some benefit is obtained where the injection pressure exceeds the normal formation back-pressure by only a slight amount. The rate of injection is preferably maintained at such a low value that equilibrium conditions are attained substantially continuously, i.e., at any given instant during the injection the pressure within the various strata which comprise the formation is substantially the same in high- and low-permeability alike. If necessary, or desired, however, a relatively high rate of liquid injection may be employed, and the well allowed to stand, either periodically during the injection period or at the end thereof, under the applied pressure until equilibrium conditions are attained.

As previously stated, the second step of the process consists in reducing the pressure within the well bore and substantially immediately thereafter, or simultaneously therewith, injecting a viscous hydrocarbon oil into the formation under such reduced pressure. The viscous oil injection pressure may have any value between that of the normal formation back-pressure and that to which the formation has been pre-pressured in the initial step of the process. Preferably, it is more or less mid-way between the two. The amount of viscous oil employed is dictated primarily by the permeabilities of the various strata which comprise the formation as well as by economic considerations, but should of course be such that a substantial quantity of the oil occupies the strata of high permeability. Preferably sufficient should be employed to achieve penetration to a depth of at least about 10 feet into the high permeability strata of the formation.

The viscous hydrocarbon oil itself must possess certain qualifications. In the first place, it must be immiscible with water. This requirement precludes use of the so-called soluble or emulsifiable oils which contain naturally-occurring or added substances which promote emulsification of the oil with connate water. The present process is thus distinguished from those processes which seek to remove water-blocks by injecting into the blocked formation an oil which contains naturally-occurring or added emulsifying or surface active agents which promote emulsification or dispersion of the connate water in the injected oil.

As will be apparent from the various considerations previously referred to, the viscosity of the injected oil (V_1) must exceed the viscosity of the oil which is indigenous to the formation being treated (V_c), i.e., V_1/V_c must exceed unity, and the extent to which certain of the desired results are attained is determined by the extent by which V_1/V_c exceeds unity. On the other hand, the absolute value of V_1 must not be so high that the pressure required to force the injected oil deep into the high permeability strata exceeds the capacity of conventional pumping equipment or the fracturing pressure of the formation. In balancing all of the various factors to the best advantage, I have found that the permanent viscosity of the injected oil should be at least about 20 times the viscosity of the connate oil under the conditions of temperature and pressure existing in the formation subject to treatment (i.e., the value of V_1/V_c should be at least about 20), but should not exceed about 2000 cps. under said conditions. The term "permanent viscosity" is employed to indicate that the viscosity does not change with passage of time. The oils employed in the practice of the present invention are thus distinguished from the thickened oils which are employed in fracturing operations and which have the property of losing viscosity with the passage of time.

To summarize the foregoing with respect to the nature of the oil which is injected from the injection well or wells into the formation selected for treatment, said oil is a hydrocarbon oil which is substantially immiscible with the water connate to said formation. It must further be free from substances which effect solution or dispersion of connate waters in said oil, and must have a permanent viscosity at least about 20, preferably between about 20 and about 1,000, times that of the connate crude petroleum but not greater than about 2000 cps. under the formation conditions.

A wide variety of oils meet the above qualifications, and any of the same may be employed. Since the process of the invention primarily involves physical rather than chemical phenomena, the chemical nature of the oil is of no consequence, i.e., it may be a petroleum oil of paraffinic, asphaltic, or mixed-base nature obtained from western, mid-continent, eastern or foreign sources. Crude petroleum is probably the cheapest, although it will be realized that crude oil taken from the same locality or field as that where the process of the invention is carried out will seldom be suitable since such local crude oil will almost invariably have substantially the same viscosity as that of the connate crude oil which is to be recovered. Heavy distillates, including pressure and vacuum distillates, are likewise suitable, as are residua and heavy thermal or catalytically cracked fractions. Such fractions and residua are preferably dewaxed and/or deasphalted prior to use. The injection oil may also be a chemically refined product such as is obtained by adsorption processes, e.g., clay percolation, or by ex-

traction with a selective solvent, e.g., sulfur dioxide, phenol, furfural, etc. In addition to oils of such types whose inherent or natural viscosity meets the stated requirements, there may also be employed oils whose requisite viscosity is due to the presence of dissolved or dispersed additive materials. It must be emphasized, however, that such additive materials must be entirely inert with respect to the connate waters with which the injected oil comes in contact. Thus, suitable viscosity-increasing additives must be water-insoluble and must not be precipitated by or otherwise react with the dissolved metal salts usually contained in connate waters. Also, for reasons previously explained, they must not promote the emulsification or dispersion of the connate water in the injected oil. These requirements dictate that the viscosity-increasing additives be non-ionic and be substantially free from surface active characteristics. Accordingly, the various thickening or gelling agents which are commonly employed in formulating viscous oils for use in fracturing processes are not suitable for use in the present process since such agents are metallic soaps (usually aluminum soaps of fatty acids) which are not only surface-active but are precipitated by the salts usually present in connate waters. Furthermore, such agents do not usually effect a permanent increase in the viscosity of the oil. Among the various types of materials which fulfill the above requirements, oil-soluble non-ionic polymers and copolymers are probably the cheapest and most widely available. A preferred class of such polymeric additives comprises natural and synthetic rubbers, particularly the rubberized polymers of isobutylene, copolymers of butadiene and acrylonitrile (Buna-N) and copolymers of isobutylene, copolymers of butadiene and styrene (Buna-S), copolymers of isobutylene and butadiene (Butyl" rubber). Also suitable are the Thiokol rubbers, polychloroprene, polystyrene, polybutadiene, polymethylmethacrylate, polyvinyl chloride, and the like. These latter materials are not especially soluble in hydrocarbon oils, but since even small amounts are effective to increase the viscosity of hydrocarbon oils to a high degree, they may be employed to advantage. Any of the various known techniques for preparing hydrocarbon oil solutions or dispersions of such polymeric materials may be employed in preparing such compounded oils.

The third step of the process consists of a conventional flooding operation in which an aqueous flooding medium is introduced into the injection well or wells and is forced out through the formation towards one or more input wells, displacing the bodies of viscous oil and the pre-pressuring liquid ahead of it. In accordance with conventional practice, the aqueous flooding medium may be fresh water, oil-field brine, ocean water, etc., and may optionally contain minor amounts of additives adapted to impart specific desirable properties to the medium. Among such optional additives there may be mentioned viscosity-increasing additives, e.g., water soluble polymers, which serve to increase the viscosity of the flooding medium and thereby increase the sweep efficiency; bactericides, such as chlorinated phenols, aldehydes and the like, which serve to prevent bacterial growth from clogging the interstices of the formation; corrosion inhibitors; surface active agents; etc.

The procedure followed in carrying out the process of the invention is for the most part conventional. Usually the formation to be flooded is isolated from the rest of the well bore by means of suitable packing devices, and the well bore is filled with the pre-pressuring fluid. The charge of viscous oil is then introduced into the well tubing and sufficient pressure is applied to force it down the tubing while displacing the pre-pressuring fluid out into the formation. When the charge of viscous oil reaches the formation, the pumping pressure is reduced so that the viscous oil is forced into the formation under reduced pressure as previously described. The

charge of viscous oil may be followed immediately by the aqueous flooding medium, or an inert liquid may be interposed between the viscous oil and the flooding medium. Such an inert liquid preferably takes the form of an emulsion of oil and water, or an oil to which an emulsifying agent has been added so that an emulsion is formed in situ from such oil and the charge of aqueous flooding medium which follows it. The interjection of an oil-water emulsion between the charge of viscous oil and the aqueous flooding medium reduces fingering of the latter through the bodies of viscous oil, and improves the efficiency and uniformity with which the flooding medium displaces the bodies of viscous oil through the formation. The oil employed in preparing such emulsion may be any mineral oil, preferably one of intermediate viscosity, and is suitably a local crude oil. Any of the many known emulsifying agents capable of emulsifying water and mineral oils may be employed; petroleum sulfonates and soaps of the same are preferred. If desired, the viscosity of the inert liquid or emulsion may be gradually reduced over the period of its injection or a plurality of inert liquids or emulsions of decreasing viscosity may be employed.

As is apparent, the invention lies in the described use of a pre-pressuring liquid and a viscous oil rather than in particular manipulative steps, and in general any of the conventional methods for injecting liquids into subterranean formation can be employed in carrying out the various steps of the present process. It will be further apparent that the process may be repeated at intervals during an extended flooding operation.

The following examples will illustrate several ways in which the principle of the invention may be applied, but are not to be construed as limiting the same.

Example I

A well in the Los Angeles basin area which constitutes the production well of a typical "five-spot" water drive produces about 250 bbls./day of 90% water-cut crude through a slotted liner from a 55-foot producing interval at bottom depth. The strata which comprise said producing interval vary in permeability from about 100 md. to about 2800 md. In order to improve production, the water-drive operation is discontinued. A 150-bbls. charge of local crude oil (viscosity = 1 cps. at formation conditions) which has previously been produced from the well is then introduced into each of the four injection wells, after which a charge of viscous oil is pumped down each of the wells on top of the charge of crude. The pumping pressure is about 2500 p.s.i.g. After about 2 hours, the 150-bbl. charges of crude have been forced into the formation and the viscous oil is opposite the formation. The pumping pressure is then reduced to 1250 p.s.i.g., and pumping is continued at such reduced pressure until about 300 bbls. of the viscous oil has been forced into the formation. The water drive operation is then resumed, employing local field brine as the driving medium. After equilibrium conditions have been obtained, the production well produces about 350 bbls./day of 70% water-cut crude. The viscous oil employed is a Duo-Sol refined vacuum distillation fraction of a western crude, and has a viscosity of about 100 cps. at formation temperature.

Example II

Five wells constituting a "five-spot" drive pattern are drilled into a producing interval which extends between 3720 and 3890 feet of depth and which comprise numerous reservoir oil-bearing and water-bearing strata of varying permeability. Using standard techniques, the production zone is isolated in each of the wells by means of suitable packers. A charge of 200 bbls. of local field brine is forced down each of the injection wells and out into the producing interval under a pressure of about 1750 p.s.i.g. Immediately thereafter a 200-bbl. charge

of a compounded viscous oil is forced down each of the injection wells and out into the interval under a pressure of about 900 p.s.i.g. The compounded oil is one prepared by dispersing poly-isobutylene (molecular weight= 250,000) in a dewaxed lubricating oil fraction with the aid of petroleum ether and acetone as secondary solvents, and thereafter diluting the resulting rubbery dispersion with kerosene. The compounded oil contains about 1.6 percent by weight of poly isobutylene, and has a viscosity of about 332 cps. at the formation temperature as compared with the viscosity of the connate oil of about 0.4 cps. Injection of the compounded oil is followed by a 150-bbls. charge of an oil-water emulsion prepared by emulsifying equal volumes of local crude oil and local field brine with the aid of a petroleum sulfonate emulsifying agent. Finally, the emulsion is followed by a conventional water flooding operation in which local field brine is injected into the producing interval from each of the injection wells at a pressure of about 950 p.s.i.g. and at a rate of about 1500 bbls./day.

Other modes of applying the principle of my invention may be employed instead of those explained, change being made as regards the methods or materials employed, provided the step or steps stated by any of the following claims, or the equivalent of such stated step or steps, be employed.

I, therefore, particularly point out and distinctly claim as my invention:

1. The method of producing petroleum from a subterranean petroleum-bearing formation which is penetrated by a production well and an injection well spaced therefrom, said formation comprising closely adjacent strata of different permeabilities extending between said production and injection wells, which method comprises introducing into said injection well an inert liquid having a viscosity not substantially greater than that of the petroleum connate to said formation; applying to said liquid a pressure substantially greater than the normal formation back-pressure and sufficient to force said inert liquid into said formation but insufficient to fracture said formation; reducing the applied pressure to a value which is intermediate between that of the normal formation back-pressure and that at which said inert liquid was forced into said formation; thereafter, but before the pressure within said strata becomes equalized at said intermediate value, injecting into said formation from the said injection well a hydrocarbon oil having a permanent viscosity at least about 20 times that of the petroleum connate to said formation but not greater than about 2000 centipoises, said hydrocarbon oil being free from agents which cause the emulsification of oil and water, and said injection being effected at said reduced pressure; and thereafter while retaining said hydrocarbon oil and said inert liquid within the formation introducing an aqueous flooding medium into said injection well and applying thereto sufficient pressure to cause it, as well as said hydrocarbon oil and said inert liquid, to flow through said formation towards said production well.

2. A method as defined by claim 1 wherein, the said insert liquid is a hydrocarbon oil.

3. A method as defined by claim 1 wherein the said inert liquid is crude petroleum.

4. A method as defined by claim 1 wherein the said viscous hydrocarbon oil is a petroleum distillate solution of a water-insoluble non-ionic polymer.

5. A method as defined by claim 1 wherein the said inert liquid is crude petroleum which has previously been produced from said formation, and the said viscous hydrocarbon oil is a petroleum distillate solution of a rubber-like hydrocarbon polymer.

6. A method as defined by claim 1 in combination with the step of injecting into the formation between said viscous hydrocarbon oil and said aqueous flooding medium an inert liquid having a viscosity between that of said viscous hydrocarbon oil and that of said aqueous flooding medium.

7. A method as defined by claim 6 wherein said inert liquid of intermediate viscosity is an emulsion of oil and water.

8. The method of producing petroleum from a subterranean petroleum-bearing formation which is penetrated by a production well and an injection well spaced therefrom, said formation comprising closely adjacent strata of different permeabilities extending between said production and injection wells, which method comprises: (1) introducing into said injection well an inert liquid having a viscosity not substantially higher than that of the petroleum connate to said formation; (2) thereafter introducing into said injection well a hydrocarbon oil having a permanent viscosity at least 20 times that of the petroleum connate to said formation but not greater than about 1000 centipoises and being free from agents which cause emulsification of oil and water; (3) applying to said hydrocarbon oil a pressure sufficient to force said inert liquid into said formation but insufficient to fracture said formation; (4) continuing to apply said pressure until substantially all of said inert liquid is forced into said formation; (5) reducing the applied pressure to a value below that applied in Step (4) but sufficient to force said hydrocarbon oil into said formation; (6) continuing the application of pressure at said reduced value until said hydrocarbon oil is forced into said formation; (7) introducing an aqueous flooding medium into said injection well while retaining said hydrocarbon oil and said inert liquid within said formation; (8) and applying to said aqueous flooding medium sufficient pressure to cause it, as well as said hydrocarbon oil and said inert liquid, to flow through said formation towards said production well.

9. A method as defined by claim 8 wherein the said inert liquid is aqueous.

10. A method as defined by claim 8 wherein the said inert liquid is a hydrocarbon oil.

11. A method as defined by claim 8 wherein the said inert liquid is crude petroleum which has previously been produced from said formation.

12. A method as defined by claim 8 wherein the amount of said inert liquid employed and the pressure applied thereto in Step (3) are sufficient to force said liquid into said formation for a distance of at least about 5 feet.

13. A method as defined by claim 8 wherein said viscous hydrocarbon oil is a petroleum distillate solution of a water insoluble non-ionic polymer.

14. A method as defined by claim 8 wherein the said inert liquid is crude petroleum which has previously been produced from said formation, and the said viscous hydrocarbon oil is a petroleum distillate solution of a rubber-like hydrocarbon polymer.

15. A method as defined by claim 8 in combination with the step, interposed between said Steps (6) and (7), of introducing into said injection well and forcing into said formation an inert liquid having a viscosity between that of said viscous hydrocarbon oil and said aqueous flooding medium.

16. A method as defined by claim 15 wherein said inert liquid of intermediate viscosity is an emulsion of oil and water.

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