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SECONDARY RECOVERY OF OIL BY PARTIALLY MISCIBLE PHASE DISPLACEMENT

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ABSTRACT OF THE DISCLOSURE

This specification discloses a method by injection of a displacing fluid for recovering oil from a subterranean formation wherein the formation is in a state of free gas saturation and the displacing fluid is, at the conditions within the formation, gaseous and only partially miscible with the oil. The method involves introducing into the formation, prior to the displacing fluid, a hydrocarbon liquid which is undersaturated relative to the free gas in the formation and miscible with the oil in the formation. This liquid, which may be crude oil, liquefied petroleum gas, naphtha, or kerosene, is introduced in a quantity only to prevent flow of the displacing fluid through the passages in the formation occupied by the free gas and less than the quantity which will pass entirely through the formation. Typical displacing fluids are carbon dioxide and enriched hydrocarbon gas.

This is a continuation-in-part of my copending application Ser. No. 308,682, filed Sept 13, 1963 and now abandoned.

This invention relates to the production of oil by secondary recovery methods. More specifically, this invention relates to the secondary recovery of oil by a method utilizing a displacement fluid which is gaseous and only partially miscible with the oil in the formation. Still more specifically, this invention relates to the recovery of oil from a subterranean formation in a state of free gas saturation by miscible displacement where the displacement fluid under the conditions within the formation is gaseous and only partially miscible with the oil.

The first production of oil from a formation is normally obtained by allowing native reservoir energy to force the oil from the formation to the surface through one or more wells. This form of oil production is generally referred to as primary recovery. The native reservoir energy may exist in the form of water drive, gas cap, or solution-gas drive, either singularly or in combination. These various forms of energy, which are inherent in most newly discovered oil-bearing formations, provide the driving force for the displacement of the oil to the surface without the necessity of providing energy from a source outside of the formation. At a time when the native reservoir energy of a formation is either nearing depletion or is depleted, it is common practice to try to obtain further oil production from the formation by secondary recovery methods which involve the addition of energy from sources outside of the formation. Without the use of secondary recovery methods, it is believed that in most instances only a minor portion of the oil present in a formation is recovered by the natural formation pressure. Among these secondary recovery methods are those which have been termed miscible slug drive methods.

In ordinarily miscible liquid slug drive methods, a liquid slug is passed through the subterranean formation from an injection well to one or more production wells by means of a driving gas forced under pressure through the formation. The material forming the liquid slug is one which is miscible not only with the oil in the formation but also with the driving gas. Liquefied petroleum gas is

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often employed as the material forming the liquid slug. However, gases which are immediately miscible with the oil in the formation, i.e., form a single phase with the oil in the formation immediately upon entering the formation, may also be employed. As a result of being miscible with the oil and the formation gas, the miscible slug as it passes through the formation defines at its leading edge a single-phase transition zone varying in composition from a solution of the miscible slug material and formation gas in the oil at its leading edge to the slug material per se as the center of the slug is approached. Thus, in these methods, the miscible slug provides a more or less distinct single-phase transition zone of flowing liquid near its leading edge. In its passage through the formation, this transition zone effects a pistonlike displacement of the oil and moves it to a production well from which it can be recovered. It is assumed that the miscible slug is miscibly displaced by a driving fluid miscible with the slug material.

While miscible slug displacement effects an increase in the amount of oil recovered from a subterranean formation, it suffers from some drawbacks. For example, the material forming the miscible slug is relatively expensive. Additionally, the material must be employed in a quantity sufficiently great that the miscible slug will maintain its integrity, or unitary character, until it reaches the production well. In many instances, therefore, the miscible operation is uneconomical.

Under certain circumstances, the use of a relatively expensive miscible fluid can be avoided. For example, a gas such as carbon dioxide or a rich natural gas which is only partially miscible with the oil within the formation may be employed. Such gas can be available in abundant supply depending upon location and thus can be relatively inexpensive. Further, such gas, even though only partially miscible with the formation oil, can form by processes of selective extraction or absorption within the formation a transition zone at its leading edge which will effectively displace the formation oil. Such transition zones are formed by concentrating intermediate molecular weight hydrocarbons such as ethane, propane, and butanes in the transition zone either by selective extraction from the oil by the gas, i.e., carbon dioxide, or by absorption from a rich gas by the oil. This transition zone, once formed, will displace the oil with an efficiency dependent upon the properties of the oil and the conditions of the formation. The gas can be followed, if desired, by a still less expensive driving fluid as is employed with a completely miscible liquid. On the other hand, where the gas is available in sufficiently large amounts at low cost, the use of a supplementary driving fluid may not be required and the gas may be employed to form the transition zone and as the driving fluid. The partially miscible gas, however, while otherwise satisfactory as a displacing fluid, cannot be regarded as a substitute for a completely miscible fluid since it cannot be used in all formations.

Most often, oil within a formation contains dissolved gas. As long as the pressure within the formation is at a sufficiently high level, this gas remains in solution with the oil. Throughout the period during which the formation is produced by primary production, the pressure within the formation steadily declines. When the "bubble point" for the particular fluid system within the formation is reached, bubbles of free gas will develop within the oil and separate out of solution. At the time the free gas begins coming out of solution with the oil in the formation, the formation starts to develop what is referred to as a condition of gas saturation. In other words, a condition is developing wherein there exists within the formation a quantity of free gas. So long as this free gas is below the "critical" gas saturation level, it does not exist actually as a continuous phase within the for-

mation. However, when the free gas condition is above the critical gas saturation level, as is usually the case in the vicinity of the injection well at the start of a secondary recovery procedure, free gas exists as a continuous, readily flowable phase within the formation. The presence of free gas in the form of bubbles but particularly in the form of a continuous phase adversely affects both the total recovery of oil and the length of the transition zone between the fluids in the formation and the displacing fluids in secondary recovery procedures which involve the use of partially miscible, gaseous displacing fluids. The transition zone referred to is the zone of mixing between the displaced oil and the displacing gas previously mentioned and the length of the zone is a measure of the quantity of displacing fluid required. Thus, the length of the zone becomes a rather important economic factor.

Where the oil in a formation is in a state of free gas saturation, the use of a gas which is only partially miscible with the oil is less effective. In these instances, the gas will not readily effect pistonlike displacement of the oil. Rather, the gas, even though partially miscible with the oil, will tend to flow rapidly through the passages of the formation occupied by high saturations of the free gas. Thus, the gas will tend to bypass the oil and mix with the oil rather than displace it. The formation of a transition zone effective in displacing the oil is thus retarded or even prevented completely and the amount of mixing between the oil and the gas is increased. As a result, displacement efficiency is impaired and the amount of partially miscible slug material required is increased. This tendency toward bypassing and mixing becomes significant at free gas saturations below the critical saturation but is much more pronounced at or above the critical saturation.

It is an object of this invention to provide a method whereby pistonlike displacement of oil in a subterranean formation in a condition of free gas saturation may be effected by employing a displacing fluid which is gaseous and only partially miscible with the oil in the formation.

It is another object of this invention to avoid the fingering of displacing fluid which is gaseous and only partially miscible with the oil in a subterranean formation through the passages of the formation occupied by a free gas phase.

These and other objects of the invention will become apparent from the following detailed description.

Summary of the invention

In accordance with the invention, oil is recovered from a subterranean formation in a condition of free gas saturation employing a displacing fluid which is gaseous and only partially miscible with the oil in the formation by injecting into the formation prior to the displacing fluid a minor quantity of a hydrocarbon material which is liquid under the conditions prevailing within the formation, is undersaturated relative to the free gas in the formation, and is miscible with the oil present in the formation.

The invention is applied to an oil-bearing formation provided with at least one injection well and at least one production well. These wells are spaced apart from each other so that the portion of the formation to which the invention is applied will generally lie between the two wells. It will be obvious, of course, that a plurality of both injection and production wells may be used.

In carrying out the first step of the invention, a quantity of the hydrocarbon material which is liquid under the conditions prevailing within the formation is introduced into the formation through the injection well. The hydrocarbon material is miscible with the oil within the formation. Further, the hydrocarbon material is undersaturated with respect to the free gas in the formation and, accordingly, the free gas in the formation will dissolve in the hydrocarbon material to form a single liquid phase. Thus, there is formed in the formation a single-phase

liquid slug consisting of the hydrocarbon material and oil and gas from the formation dissolved in the hydrocarbon material. Examples of hydrocarbon materials which may be used in the first step are crude oil, liquefied petroleum gas, naphtha, and kerosene. Undersaturation of crude oil may be effected by carrying the oil through a positive step of degassing, which may comprise no more than exposing the oil to the atmosphere until any gas dissolved therein has passed out of solution. It is not necessary that the hydrocarbon material be completely miscible with the displacing fluid to follow.

The quantity of hydrocarbon material necessary to carry out the invention effectively is quite small. This quantity need be only that which will form the single-phase liquid slug of hydrocarbon material, oil, and gas in the formation in the vicinity of the injection well. This slug acts as a buffer zone between the displacing fluid and the reservoir gas and bypassing of the displacing fluid subsequently injected is prevented. The displacing fluid, being partially miscible with the oil in the formation, through processes of selective extraction or absorption previously mentioned, forms a transition zone which will effect pistonlike displacement of the oil. The displacing fluid is also at least partially miscible with the hydrocarbon material employed to form the single-phase liquid slug and thus is at least partially miscible with the liquid slug. The single-phase liquid slug formed of the hydrocarbon material, the free gas, and the oil serves only to separate the displacing fluid from the free gas in the formation and thus reduce bypassing of the oil by the displacing fluid and mixing of the oil and the displacing fluid while the displacing fluid is developing an effective transition zone either by selective extraction of intermediate molecular weight components from the oil by the carbon dioxide or by absorption of these components by the oil from the rich gas as the case may be. Once the transition zone is developed, it displaces oil and gas ahead of it and the oil bank ahead of the transition zone continues to grow. Thus, the recovery procedure is no longer affected by the free gas in the formation since the displacing fluid and the free gas can no longer come into contact with each other. Moreover, the displacing fluid does not finger through the passages of the formation occupied by the free gas and mix with the oil but rather effects pistonlike displacement of the oil.

Amounts of hydrocarbon material greater than that necessary to form the single-phase liquid slug in the vicinity of the injection well, of course, could be employed. However, where such greater amounts are employed, the economies to be effected by the invention become lessened. The transition zone can be formed before the displacing fluid has moved into the formation more than twenty-five feet from the injection well. Only sufficient hydrocarbon material need be employed to maintain a single-phase liquid slug for this distance. Generally, the hydrocarbon material may be employed in an amount of about two barrels of liquid per foot of formation penetrated by the injection well. In any case, the amount of hydrocarbon material injected into the formation should be no greater than about 0.5 percent of the hydrocarbon pore volume of the formation. These amounts of about two barrels per foot of formation or less than about 0.5 percent of the hydrocarbon pore volume of the formation will be insufficient to form a slug which will pass entirely through the formation to the production well.

For purposes of definition, the term "hydrocarbon pore volume" as used herein means that volume of the pore space in a formation which was originally occupied by the hydrocarbon, whether in the gaseous or liquid phase, or both, and which is traversed by the displacing fluid. It is to be understood that such definition does not contemplate the existence of a "gas cap," and should such exist within a formation its volume would not be taken into consideration in the determination of the hydrocarbon pore volume of the formation.

Subsequent to the introduction of the hydrocarbon material into the formation, the displacing fluid is injected into the formation through the injection well. An example of a partially miscible, gaseous displacing fluid is carbon dioxide. By carbon dioxide is meant any gas which contains carbon dioxide in the amount of at least 50 percent by volume. Pure carbon dioxide can be employed. However, a gaseous mixture of methane and carbon dioxide, the carbon dioxide being in the amount of more than 50 percent by volume, such as obtained from a subterranean formation in West Texas, may be employed. Another example of a displacing fluid is an enriched hydrocarbon gas of insufficient richness to make it immediately miscible with the formation oil, i.e., methane mixed with insufficient amounts of higher hydrocarbons to effect miscibility. The amount of displacing fluid injected into the formation should be sufficient to form a slug of the displacing fluid which will retain its integrity or unitary character upon passing entirely through the formation from the injection well to the production well. This amount may be, in quantitative terms, from about 1 to about 25 percent of the hydrocarbon pore volume of the formation.

The displacing fluid may, as previously described, be followed by a driving fluid. A driving fluid can be employed where the amount of displacing fluid available is insufficient or where economics require the use of minimum quantities of the displacing fluid. Driving fluids which may be employed include natural gas, water, or air. Sufficient driving fluid, where employed, is injected into the formation until it is believed that substantially all of the recoverable oil has been displaced from the formation through the production well. This will ordinarily have occurred when the effluent from the production well is substantially all driving fluid.

Table I, below, illustrates the results of experimental runs performed during partially miscible flooding programs carried out in the laboratory. The flooding programs were executed in 50-foot packs of unconsolidated sand within laboratory test cells. In runs 1-3, where the free gas saturation of the pack was zero, the length of the mixing zone ranged from 11.0 to 12.0 feet, with the percentage of oil recovery running from 88.6 to 92.8 percent. In runs 4 and 5, the percentage of free gas saturation was increased to 18.3 and 19.4, respectively, with the length of the mixing zone increasing to 26.0 feet and 31.2 feet and the percentage of oil recovery decreasing to 69.4 and 68.0. The increase of the free gas saturation caused an increase in the mixing zone length, with a direct decrease in the percentage of oil recovery. In run 6, the free gas saturation was increased to 28.3 percent; however, a small slug of undersaturated hydrocarbon material was injected in advance of the carbon dioxide flooding agent with a resultant decrease in the length of the mixing zone to 22 feet and an increase in oil recovery to 79.9 percent. Thus, the injection of the undersaturated hydrocarbon material effected, even with an increase in free gas saturation, a decrease in transition zone length together with an increase in oil recovery.

TABLE I

Run No.	Percent Free Gas Saturation	Mixing Zone Length in ft.	Percent Oil Recovery	Remarks
1.....	0	11.3	92.8	
2.....	0	11.0	88.6	
3.....	0	12.0	90.3	
4.....	18.3	26.0	69.4	
5.....	19.4	31.2	68.0	
6.....	28.3	22.0	79.9	Small slug of hydrocarbon material, undersaturated with respect to formation gas, ahead of CO ₂ slug.

While it is not intended that the invention be limited to any particular technological theory of operation, it is be-

lieved that the improvement in oil recovery through the provision of the undersaturated hydrocarbon material buffer zone is due to separation of the injected gaseous displacing fluid from the in-place gas in the formation until a transition zone, between the displacing fluid and oil, capable of displacing oil and gas is developed by selective extraction and an appreciable oil bank is established ahead of the injected displacing fluid. Separation of the two gases prevents the gaseous displacing fluid from flowing preferentially through the passages occupied by the in-place gas and thus bypassing the oil in place. The reduction in the mixing zone length is accomplished by avoiding the period of rapid mixing which occurs in the initial part of a flood because of the bypassing of large quantities of oil by the gaseous displacing fluid when the injected fluid is in contact with the in-place gas. When the displacing fluid bypasses oil, a large area of contact is established between the displacing fluid and oil and rapid mixing occurs. The separation of the gaseous displacing fluid from the in-place gas is accomplished through the process of displacing part of the gas by the undersaturated liquid slug of hydrocarbon material and by solution of that part of the in-place gas which cannot be displaced ahead of the liquid slug. Thus, there is no free gas phase within the liquid hydrocarbon slug.

Having thus described my invention, it will be understood that such description has been given by way of illustration and example and not by way of limitation, reference for the latter purpose being had to the appended claims.

What is claimed is:

1. In a method of secondary recovery of oil from a formation having at least one injection well and at least one production well wherein there is injected into said formation through said injection well for pistonlike displacement of said oil to said production well a displacing fluid which at the conditions within said formation is gaseous and is only partially miscible with said oil but wherein said formation is in a state of free gas saturation whereby said displacing fluid does not effect pistonlike displacement of said oil to said production well but tends rather to flow through the passages in said formation occupied by free gas and bypass and mix with rather than displace said oil and adversely affects the total recovery of said oil, the steps which comprise:

(a) introducing into said formation through said injection well a hydrocarbon material, said hydrocarbon material being undersaturated relative to said free gas in said formation and which under the conditions prevailing within the formation is liquid, in a quantity only to prevent flow of said displacing fluid through the passages in said formation occupied by said free gas and thereby prevent bypassing and mixing with rather than displacing of said oil and less than the quantity which will pass entirely through said formation to said production well,

(b) thereafter introducing into said formation through said injection well said displacing fluid which is gaseous and only partially miscible with said oil in said formation at the conditions within said formation in a quantity to form a slug which will pass entirely through said formation and effect displacement of said oil between said injection well and said production well, and

(c) driving said slug of displacing fluid through said formation to said production well to displace said oil from said formation through said production well.

2. A method according to claim 1 wherein said displacing fluid is carbon dioxide.

3. A method according to claim 2 wherein the quantity of said carbon dioxide is in an amount ranging from about 1 to about 25 percent of the hydrocarbon pore volume of said formation.

4. A method according to claim 1 wherein said displac-

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ing fluid is an enriched gas of insufficient richness to be immediately miscible with said oil in said formation.

5. A method according to claim 1 wherein the quantity of said hydrocarbon material is not greater than about 0.5 percent of the hydrocarbon pore volume of said formation.

6. A method according to claim 1 wherein the quantity of said hydrocarbon material is about two barrels of liquid per foot of formation at said injection well.

7. A method according to claim 1 wherein a driving fluid is injected into said formation through said injection well following said displacing fluid.

8. A method according to claim 1 wherein said displacing fluid is driven through said formation to said production well by introducing into said formation through said injection well a driving fluid and continuing introduction of said driving fluid until the effluent from said production well is substantially said driving fluid.

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