July 7, 1964 B. HABERMANN 3,139,929

SECONDARY RECOVERY BY MISCIBLE FLUID DISPLACEMENT

Filed Nov. 30, 1959 2 Sheets-Sheet 1

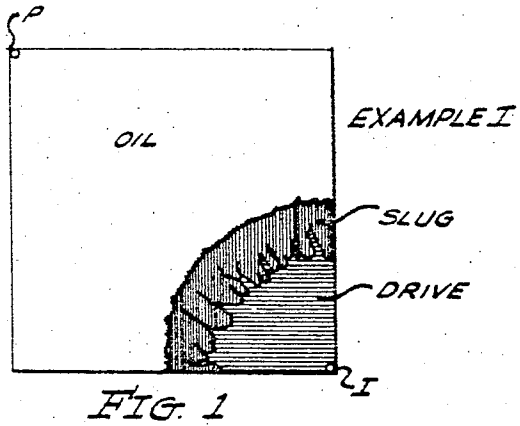


FIG. 1

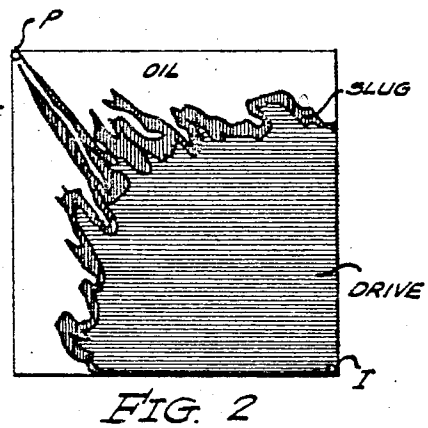


FIG. 2

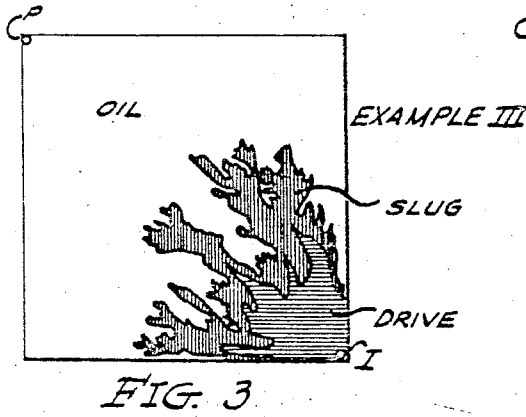


FIG. 3

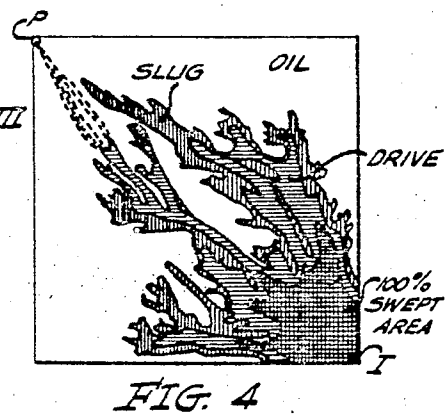


FIG. 4

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SECONDARY RECOVERY BY MISCIBLE FLUID DISPLACEMENT

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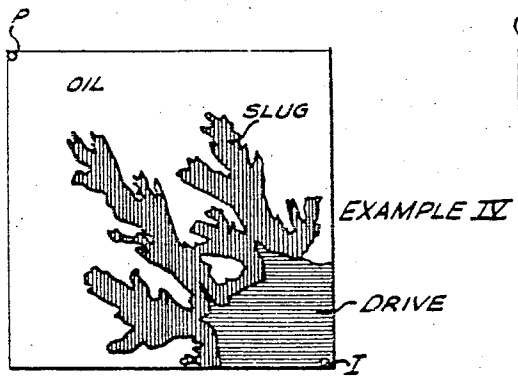


FIG. 5

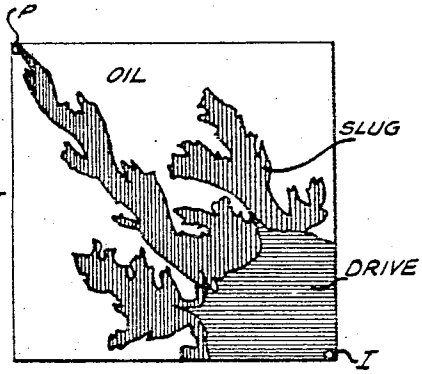


FIG. 6

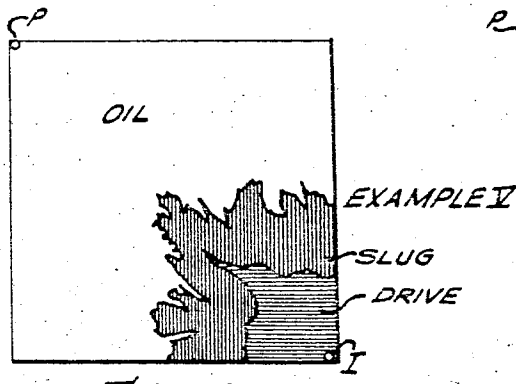


FIG. 7

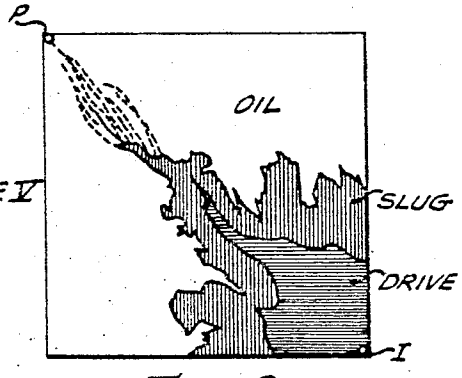


FIG. 8

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SECONDARY RECOVERY BY MISCIBLE FLUID DISPLACEMENT

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9 Claims. (Cl. 166—9)

This invention relates to secondary recovery of petroleum from subterranean reservoirs. Specifically, it relates to a miscible fluid displacement method of secondary recovery having improved areal sweep efficiency, and comprises simultaneous injection of water with the miscible fluid and the drive gas.

In attempts to recover petroleum from subterranean reservoirs by secondary recovery, much attention has recently been focused on the miscible fluid slug displacement method. In this method, a fluid (herein termed a "displacement fluid") miscible with the reservoir crude oil is injected into the formation from an injection well and is forced through the formation to drive or carry the crude oil towards a suitably located production well. Examples of suitable displacement fluids are LPG, propane, butane, isobutane, pentane, isopentane and petroleum distillates. Since such fluids are relatively expensive, they are in turn forced through the formation by a less expensive driving fluid which is soluble therein or miscible therewith, e.g., natural gas, methane, ethane or reservoir gas. Usually, the driving fluid is gaseous at reservoir conditions. The displacement fluid is thus employed in the form of a slug interposed between the driving fluid and the crude petroleum, and is provided only in an amount sufficient to insure separation of the driving fluid and the petroleum.

Although miscible fluid displacement provides high oil recovery from the swept area, much difficulty has been experienced in obtaining a satisfactory areal sweep of the reservoir. The poor areal sweep of the displacement fluid slug has been found to be related to high mobility ratios between the displacement fluid and the oil, between the displacement fluid and the drive fluid, and between the oil and the drive fluid. The mobility ratio is defined by the following equation:

$$M=\frac{\frac{k_2}{\mu_2}}{\frac{k_1}{\mu_1}}=\frac{\mu_1}{\mu_2}\times\frac{k_2}{k_1}$$

where

M=mobility ratio;

μ_2,μ_1=viscosity of displacing fluid and displaced fluid, respectively;

k_2,k_1=permeability of the formation with respect to the displacing fluid and displaced fluid, respectively.

Laboratory tests on miscible displacement in a simulated five spot pattern over a wide range of mobility ratios have shown that the maximum sweep efficiencies (before breakthrough of the miscible fluid) are achieved at the lowest mobility ratios; ratios of one or less being necessary to sweep at least 70 percent of the core area, with ratios between 1 to 10 sweeping only 70 to 43 percent of the area. From this test work, it can be seen that the areal sweep efficiency of a miscible displacement operation is proportional to the mobility ratios in the system. The preceding equation shows that these mobility ratios are in turn directly proportional to the ratio of the displaced fluid viscosity to the displacing fluid viscosity, μ_1/μ_2, and inversely proportional to the ratio of the formation permeability with respect to the displacing fluid to its permeability with respect to the displaced fluid, k_2/k_1.

In addition to their adverse effect on areal sweep efficiencies, high mobility ratios between the fluids cause fingering, resulting in a high degree of mixing between the fluids. When this occurs, the displacement fluid becomes enriched with reservoir oil and loses its miscibility with the drive fluid, and true miscible displacement is no longer achieved.

In most miscible fluid displacement processes, the ratio of the formation permeabilities with respect to the miscible fluid and the reservoir oil, k_s/k_o, is fixed by the inherent characteristics of the formation. Generally, this ratio is greater than one and (is hence adverse to high sweep efficiency) because the permeability of the formation with respect to the reservoir oil is lowered by the presence of gas bubbles in the reservoir oil. This condition, referred to as "free gas saturation," occurs whenever the reservoir pressure is below the bubble point pressure of the reservoir fluids. This can occur naturally but is usually the result of pressure depletion during primary recovery.

Previously, attempts to improve the mobility ratio between the displacement fluid and the reservoir oil have centered about methods for reducing the ratio of the viscosity reservoir oil to that of the displacement. Thus, it has been proposed that the viscosity of the displacement fluid be increased by the addition thereto of crude oil or crude oil distillates. A refinement of this is the technique of adding a viscous oil to the slug of displacement fluid in varied amounts to obtain a slug having graduated bands of successively lower viscosity from its leading to trailing edge, thereby avoiding any single sharp transition in vscosity between the oil and slug or between the slug and the drive fluid. These methods, however, are beset by many problems, among which is that addition of crude oil or distillates to the miscible slug destroys its miscibility with the drive fluid, and true miscible displacement is lost. When this occurs, the drive fluid tends to finger through the slug into the oil phase towards the producing well rather than advance as a smooth front, and much of the slug and oil is bypassed. Another factor to be considered in any commercial process is the impracticality of adding the necessary amount of oil to the displacement fluid to increase its viscosity sufficiently. If relatively expensive distillates are not employed and a portion of the produced crude oil is used as the viscosity additive, it is apparent that the viscosity of the displacement fluid cannot be as great as the reservoir oil viscosity; as a practical limit, the viscosity of the displacement fluid is much less than that of the reservoir oil. Yet, if the most favorable mobility ratios are to be obtained, the viscosity of the displacement fluid must be made at least as great as that of the reservoir oil, and in those cases where the formation has a low relative permeability to the oil due to free gas saturation, the viscosity of the displacement fluid must be made greater than that of the reservoir oil. Actual recovery data obtained by laboratory displacements in core samples simulating reservoir conditions have shown that substantially no improvement in areal sweep efficiency can be achieved by the technique of increasing the viscosity of only the displacement fluid slug.

It has also been proposed that the mobility of the drive fluid be reduced so as to decrease the mobility ratio between the displacement fluid and the drive fluid. In practice, it has been found that although the areal sweep of the drive fluid is thus improved, the displacement fluid slug fingers severely into the reservoir oil so that it no longer separates the drive fluid from the reservoir oil. When this occurs, miscibility is lost and only a fraction of the oil is recovered from the swept area.

It is the general purpose of this invention to improve the areal sweep efficiency of a miscible fluid displacement process and to prevent fingering and bypassing of the reservoir oil by the displacement fluid.

The aforementioned purpose is achieved in accordance with the invention by admixing water with both the displacement fluid and the drive fluid. The presence of water in these two phases decreases the relative permeability of the formation with respect to both the displacement fluid and the drive fluid, and thus reduces the mobility ratios between the displacement fluid and the reservoir oil and between the drive fluid and the displacement fluid. This results in a greatly improved areal sweep efficiency for the process.

The invention is described in detail in the following paragraphs and examples which refer to the figures of which:

FIGURES 1 and 2 illustrate the areal sweep patterns obtainable by the invention;

FIGURES 3 and 4 illustrate the areal sweep pattern obtained in miscible fluid displacements embodying two slugs of fluids having successively lower viscosities;

FIGURES 5 and 6 illustrate the areal sweep pattern typical of that obtained in a miscible fluid displacement process employing a miscible slug and a water drive;

FIGURES 7 and 8 illustrate the areal sweep patterns obtained by miscible displacement employing three slugs of successively lower viscosity miscible liquids and a gas drive.

The amount of water to be added to each of the displacement and drive fluids can be calculated for each reservoir from the water and fluid viscosities, the relative permeability of the formation to water and the fluids, the water saturation in each fluid, and the amount of interstitial water present in the reservoir. Generally, the amount of water to be injected with the displacement fluid is between about 0.5 and 10 barrels per barrel measured at standard conditions and the amount of water to be admixed with the drive fluid is between about 0.75 to 15 barrels per thousand cubic feet at standard conditions. Conveniently, the mixtures are obtained by simultaneously injecting the water and the fluid in question into the reservoir, preferably at equal velocities.

The admixture of water with a given fluid has a striking effect on the mobility of that fluid. For instance, if 1.28 barrels of water are injected into a typical oil-bearing formation along with each barrel of a propane-rich displacement slug, the mobility of the slug under a typical reservoir condition is reduced from about 1700 millidarcies/centipoise to about 100 millidarcies/centipoise. Similarly, the injection of 2.08 barrels of water along with each thousand cubic feet of a drive fluid consisting of reservoir gas reduces the gas mobility from about 2900 millidarcies/centipoise to about 125 millidarcies/centipoise. To attain equivalent reductions in mobilities by increasing only the viscosities of the respective fluids would require a 1700 percent increase in the viscosity of the propane-rich slug and a 2320 percent increase in the gas viscosity. It is, of course, apparent that such increases are not possible by the heretofore suggested methods of adding hydrocarbon oil fractions to the fluids.

Even greater decreases in mobility of the injected water-fluid mixtures can be obtained by increasing the viscosity of the water by dissolving a viscosity-increasing additive therein. Preferably, the additive is a water-soluble partially hydrolyzed acrylamide polymer. The latter material is a water-soluble acrylamide polymer which has been hydrolyzed to such an extent that between about 0.8 and 10 percent of the amide groups have been converted to carboxyl groups. As herein employed, the term "acrylamide polymer" is inclusive of the homopolymers of acrylamide, i.e., polyacrylamide, and water-soluble copolymers of acrylamide with up to about 15 percent by weight of other polymerizable vinyl compounds, such as the alkyl esters of acrylic and

methacrylic acids, methacrylamide, styrene, vinyl acetate, acrylonitrile, methacrylonitrile, vinyl alkyl ethers, vinyl chloride, vinylidene chloride, etc. In addition to the aforementioned limitation on the extent of hydrolysis, the suitable acrylamide polymers are of sufficiently high molecular weight that an 0.5 percent by weight aqueous solution thereof has a viscosity of at least 4 centipoises Ostwald at 21.5° C. A commercially available polymer meeting these requirements is marketed by The Dow Chemical Company under the name "Separan." The above-mentioned polymers are preferred since they form stable solutions and do not easily precipitate when heated or when in the presence of mineral anions and cations. However, the use of any other water-soluble material which forms a stable viscous aqueous solution is also within the scope of the present invention; examples of such materials include polyvinyl alcohol, carboxymethyl cellulose, sucrose, polyethylene oxide, etc. When employing an aqueous solution of these polymers, incremental extent to which the mobility is decreased is proportional to the difference between the viscosity of the polymer solution and the viscosity of water. Generally, this can result in reducing the mobilities from 2 to 10 times more than the reduction possible by injection of only water with the displacement and driving fluid, so that the mobilities of each of the injected fluids can be made equal to or less than that of the reservoir oil.

The preceding discussion has been based on the assumption that the mixtures of water and displacement and driving fluids will remain homogeneous. Actually, a certain amount of gravity separation will occur, and the water will tend to settle to the lower strata. According to a preferred mode of operation, the effects of gravity separation are countered by injecting the water into the upper strata of the reservoir and injecting the displacement and driving fluids into lower lying strata.

The invention will now be described by reference to miscible displacement in a reservoir having a temperature of 260° F., a pressure of 2,000 p.s.i., and 16 percent free gas saturation in the oil phase. The viscosity of the oil in the reservoir is 0.66 centipoise and the relative permeability of the formation to the oil is 83 percent of its permeability to oil with no gas saturation.

EXAMPLE I

The invention as applied to this reservoir comprises the simultaneous injection of water with the displacement slug and with the drive fluid. The displacement fluid comprises a mixture of 80 volume percent propane and 20 volume percent reservoir gas, while the drive fluid comprises a methane-rich reservoir gas. To obtain equal water and displacement fluid velocity, 1.28 barrels of water are injected with each barrel of displacement fluid, and to obtain equal water and gas velocities in the drive phase, 2.08 barrels of water are injected per thousand cubic feet of reservoir gas. The following mobility ratios are thereby obtained:

Table I

Position:	Mobility ratio
Overall, between the oil and water+drive fluid	1.99
Between the oil and water+displacement slug	1.59
Between the water+displacement slug and the water+drive fluid	1.25

To determine the flow pattern achieved under these conditions, a laboratory study was made displacing fluids from a consolidated sandstone plate sealed between clear sheets of plastic and representative of a quarter section of a five spot pattern. Inlet and outlet holes corresponding to inlet well I and production well P, were provided at opposite corners of the assembly, and suitable connections permitted liquids to be forced into the sandstone plate and through the same towards the outlet connection. This assembly was supported in a horizontal plane above a light source, and a camera was positioned directly above the assembly to photograph the flow of

fluids, colored for identification, as they were passed from the inlet to the outlet connection. Cooled air was blown across the bottom surface of the assembly to prevent the hot light source from heating the assembly during a test run. Color slides or color movies were made during the tests to evaluate the flow patterns, and the outlet flow was measured to determine the amount of oil recovered. By this method a continuous record of the flow pattern was obtained. These photographs are depicted by FIGURES 1 to 8 for varied flow conditions when the aforementioned mobility ratios were duplicated, the flow pattern obtained at 10 percent pore volume of displacement fluid injected is shown in FIGURE 1 and that obtained at breakthrough of the displacement slug is shown by FIGURE 2. The recovery at slug breakthrough was 58.4 percent of the total amount of "oil" in the core. At drive fluid breakthrough the recovery was 76.5 percent.

EXAMPLE II

The aqueous polymer embodiment of the invention as applied to this reservoir comprises the simultaneous injection of a polymer solution with the displacement and drive fluids. A typical polymer solution having a viscosity of 0.5 centipoise at reservoir conditions, or only twice that of water alone, is employed at an injection ratio of 1.60 barrels per barrel of the displacement fluid and at 2.59 barrels per thousand cubic feet of the drive fluid at standard conditions. The following mobility ratios are thereby obtained:

Table 2

Position:	Mobility ratio
Overall, between the oil and aqueous polymer+drive fluid	1.06
Between the oil and aqueous polymer+displacement slug	0.93
Between the aqueous polymer+displacement slug and the aqueous polymer+drive fluid	1.14

A laboratory test duplicating the aforementioned mobility ratos in a sandstone core similar to that employed in Example I provided a 71 percent recovery before breakthrough of the displacement fluid into the producing well.

EXAMPLE III

For comparison purposes, the flow pattern obtained by a miscible displacement process typical of conventional practice was studied in the laboratory. This typical prior art method comprises injection of a 10 percent pore volume slug of 80 percent propane mixed with 20 percent reservoir gas, followed by a reservoir gas drive. The following mobility ratios are obtained between the phases:

Table 3

Position:	Mobility ratio
Overall, between the oil and gas drive fluid	46.8
Between the oil and displacement slug	27.4
Between the displacement slug and drive fluid	1.7

The laboratory test was on a sandstone core model similar to that employed in Example I and duplicated the aforementioned mobility ratios. The results from this test are depicted by FIGURES 3 and 4 which respectively show the flow patterns obtained after 20 pore volume percent of the displacement fluids had been injected into the well in the lower right-hand corner, and at breakthrough of the displacement fluids into the production well at the upper left-hand corner. The drive fluid breakthrough shown by the dashed lines extending to the producing well occurred when only 31.2 volume percent of the "oil" had been recovered, or only about 41 percent of the recovery attained when practicing the process of the invention.

EXAMPLE IV

Again, for comparison to the invention and to evaluate the flow pattern such as might be obtained by using a low viscosity propane slug and a water drive fluid in a typical reservoir, another test was made. The following mobility ratios are typical of what would be encountered under reservoir conditions:

Table 4

Position:	Mobility ratio
Overall, between the oil and water+drive fluid	1.0
Between the oil and the propane slug	38.0
Between the propane slug and the water+drive fluid	0.0265

A laboratory test was conducted duplicating the mobility ratios of Table 4. The oil recovery at breakthrough was 23.6 percent of the oil in place, or only about 31 percent of the recovery attainable with the invention. The flow patterns at 20 percent pore volume of fluid injected and at breakthrough are shown by FIGURES 5 and 6, respectively. FIGURES 5 and 6 show extreme fingering of the slug phase through the oil with poor areal sweep of the miscible slug. Continued displacement in this case showed a relatively high areal sweep of the drive fluid because the mobility ratio between the oil and drive is equal to 1. However, because the miscible slug fingered ahead of the drive and was not retained as a hand between the drive and oil phases substantial amounts of oil was bypassed and left behind as residual oil in the swept area. This loss of miscible fluid between the phases can be seen in the right-hand side of FIGURE 6.

EXAMPLE V

To study another miscible slug technique typical of prior art practice for comparison to the invention a laboratory test was conducted duplicating the mobility ratios obtained under reservoir conditions when employing a miscible fluid slug gradated into three bands of successively lower viscosity. Such a slug is obtained by adding varied amounts of a high viscosity crude to separate bands of a propane-rich miscible slug. The slug is usually driven with a low viscosity reservoir gas and the following mobility ratios prevail:

Table 5

Description:	Mobility ratio
Overall, oil to drive	75.0
Between oil and slug 1	3.0
Between slug 1 and slug 2	2.9
Between slug 2 and slug 3	3.0
Between slug 3 and drive	2.9

The flow pattern obtained in the laboratory test duplicating the aforementioned mobility ratios and after all three slugs had been injected is shown in FIGURE 7 at 25 percent pore volume of fluids injected. In FIGURE 8 the flow pattern at breakthrough is shown when 25.5 percent of the oil was recovered; only about 33 percent of the recovery possible with the invention.

The preceding examples have demonstrated that the invention which comprises the simultaneous injection of water or an aqueous polymer solution with a miscible displacement fluid and a drive fluid permits the use of low mobility ratios and thereby attains high reservoir oil recovery. This improvement is shown to be attainable only with the invention, and other methods directed to increasing the viscosity of the miscible slug or to increasing the viscosity of the gas drive do not achieve any comparable results; in fact, the results tend to show that these methods are adverse to high oil recovery.

Having disclosed and illustrated my invention, I therefore claim:

1. The method of obtaining a high areal sweep efficiency in a displacement process for the recovery of oil from a subterranean reservoir which is penetrated by at least an injection well and a withdrawal well, which method comprises: simultaneously injecting into said

reservoir through said injection well a slug of water and a slug of a hydrocarbon which is liquid and miscible with said oil under reservoir conditions, the amount of said water being between about 0.5 and about 10 barrels per barrel of said hydrocarbon, controlling the amount of water so injected to provide a velocity of water through said reservoir about equal to the velocity of said hydrocarbon liquid through said reservoir; forcing said slug of water and said slug of hydrocarbon through said reservoir towards said withdrawal well by simultaneously injecting into said injection well water and a drive fluid miscible with said hydrocarbon liquid, the amount of said water injected with said drive fluid being between about 0.75 and about 15 barrels per thousand cubic feet of said drive fluid, controlling the amount of water so injected with said drive fluid to provide a water velocity in said reservoir about equal to the velocity of said drive fluid therethrough, and withdrawing displaced oil from said reservoir through said withdrawal well.

2. The method of claim 1 wherein the said hydrocarbon liquid is selected from the group consisting of LPG, propane, butane, isobutane, pentane, isopentane, crude oil and crude oil distillates.

3. The method of claim 1 wherein said drive fluid is gaseous at reservoir conditions.

4. The method of claim 3 wherein said drive fluid is selected from the group consisting of natural gas, methane, ethane and reservoir gas.

5. The method of claim 1 wherein the said water contains a dissolved viscosity-increasing additive.

6. The method of claim 5 wherein said viscosity-increasing additive is a water soluble acrylamide polymer which has been hydrolyzed to the extent that between about 0.8 and 10 percent of the amide groups have been converted to carboxyl groups.

7. The method of obtaining high areal sweep efficiency in a displacement process for the recovery of oil from a subterranean reservoir which is penetrated by at least an injection well and a withdrawal well which comprises injecting water into the upper portion of said reservoir through said injection well while simultaneously injecting into the lower portion of said reservoir through said injection well a hydrocarbon which is liquid and miscible

with said oil under reservoir conditions, the amount of said water being between about 0.5 and about 10 barrels per barrel of said hydrocarbon, controlling the amount of water so injected to provide a velocity of water through said reservoir about equal to the velocity of said hydrocarbon liquid through said reservoir; forcing said water and said hydrocarbon through said reservoir towards said withdrawal well by continuing to inject said water into the upper region of said reservoir through said injection well and simultaneously injecting into the lower portion of said reservoir a drive fluid which is miscible with said hydrocarbon liquid, the amount of said water injected with said drive fluid being between about 0.75 and about 15 barrels per thousand cubic feet of said drive fluid, controlling the amount of water so injected with said drive fluid to provide a water velocity in said reservoir about equal to the velocity of said drive fluid therethrough, and withdrawing displaced oil from said reservoir through said withdrawal well.

8. The method of claim 7 wherein the said hydrocarbon liquid is selected from the group consisting of LPG, propane, butane, isobutane, pentane, isopentane, crude oil and crude oil distillates, and said drive fluid is selected from the group consisting of natural gas, methane, ethane, carbon dioxide, air and nitrogen.

9. The method of claim 7 wherein said viscosity-increasing additive is a water soluble acrylamide polymer which has been hydrolyzed to the extent that between about 0.8 and 10 percent of the amide groups have been converted to carboxyl groups.

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