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SECONDARY RECOVERY OF OIL FROM A SUBTERRANEAN FORMATION

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This invention relates generally to the recovery of oil from subterranean reservoirs. More specifically, this invention is directed to a method of recovering oil by a miscible phase displacement technique wherein the flood efficiency is improved by the use of carbon dioxide.

When a well is completed in a subterranean reservoir, the oil present in the reservoir is normally removed through the well by primary recovery methods. These methods include utilizing native reservoir energy in the form of water or gas existing under sufficient pressure to drive the oil from the reservoir through the well to the earth's surface. This native reservoir energy most often is depleted long before all of the oil present in the reservoir has been removed from it. Additional oil removal has been effected by secondary recovery methods of adding energy from outside sources to the reservoir either before or subsequent to the depletion of the native reservoir energy.

Miscible phase displacement techniques comprise a form of enhanced recovery in which there is introduced into the reservoir through an injection well a fluid or fluids which are miscible with the reservoir oil and serve to displace the oil from the pores of the reservoir and drive it to a production well. The miscible fluid is introduced into the injection well at a sufficiently high pressure that the body of fluid may be driven through the reservoir where it collects and drives the reservoir oil to the production well. The present invention is particularly concerned with a miscible slug type of miscible phase displacement.

In one form of the miscible slug method, a liquefied hydrocarbon slug is developed within the reservoir by introducing through the injection well a condensable hydrocarbon, such as liquefied petroleum gas, propane, or butane, at such a pressure that the hydrocarbon will be reduced to the liquid phase or will remain in the liquid phase. Also, a normally liquid hydrocarbon, such as light naphtha, may be introduced into the formation. The liquefied hydrocarbon slug is miscible with the reservoir oil and is driven through the formation to recover the oil. Other miscible materials may be employed, such as a diluted hydrocarbon slug comprising the above-identified condensable hydrocarbons diluted with natural gas. The diluted slug may be a liquid or it may be diluted to the extent that it is an enriched gas which will be miscible with the reservoir oil. In carrying out the miscible slug technique, a driving gas is normally injected into the formation behind the hydrocarbon fluid slug in order to drive the slug through the reservoir formation to the production well. Generally, the miscible slug technique is carried out at pressures of about 1000 pounds per square inch gauge and higher.

In carrying out the miscible slug technique, it has been found that serious problems sometimes develop with respect to maintaining a uniform flood front as the liquid progresses through the formation toward the production well. The uniformity to which the flood pattern, that is, the pattern assumed by the body of displacing liquid, may be held is generally referred to as the sweep efficiency of the flood. When the flood breaks away from a pattern having a uniform front boundary, generally a portion or portions of the flood will prematurely advance to the production well, resulting in the leaving behind of substantial quantities of reservoir oil. This unevenness of flood boundary is often referred to as "fingering." The sweep efficiency of a flood pattern is considered from the standpoint of both the horizontal and the vertical. The horizontal pattern of a flood, that is, the configuration of the flood pattern in a horizontal plane extending through the formation perpendicular to the injection and production wells, is generally referred to as the areal sweep. The flood pattern along a perpendicular plane extending through the formation between the injection and production wells is referred to as the vertical sweep. The horizontal and vertical sweep efficiencies of a flood pattern are influenced by several factors including the mobility ratio of the displacing to the displaced fluid, which in essence is a measurement of the relative ease with which the fluids move through the formation. If a fluid which is not very mobile is being displaced by a fluid which is very mobile, the result is a very inefficient sweep pattern in which rapid fingering develops, with the very mobile fluid advancing in finger-shaped extensions into and ahead of the fluid which is being displaced. For example, if a low viscosity gas is being used to displace a viscous oil, obviously the gas will develop into a number of fingerlike patterns which will rapidly advance through the body of oil and ultimately reach the production well leaving behind substantial portions of the oil. The mobility of reservoir oil and the fluids employed to displace the oil is directly affected by the viscosity of these materials. Thus, it would seem that if the viscosities of displaced and displacing fluids can be altered to the extent that differences of any magnitude along any particular line or zone in a flood will be minimized, the flood pattern will be improved.

It is one object of the present invention to provide an improved method for the recovery of oil from a subterranean reservoir. It is another object of the invention to provide an improved miscible phase displacement technique for recovering oil from a subterranean reservoir. It is a still further object of the invention to provide a miscible liquid hydrocarbon slug type of miscible phase displacement wherein the sweep efficiencies of the method are improved.

In accordance with the invention, reservoir oil is recovered from a formation through a production well by injecting into the formation through an injection well a quantity of carbon dioxide which is displaced by a liquid hydrocarbon slug driven by a fluid displacing material.

The first step in the method of the invention is the introduction of carbon dioxide through an injection well into the formation from which oil is to be recovered. The carbon dioxide preferably is introduced into the injection well in the liquefied state because less energy is required than when handling it in the gaseous state. As the liquid carbon dioxide descends in the wellbore, it undergoes a naturally increasing temperature, causing it to become gaseous either in the wellbore or in the formation in the immediate vicinity of the wellbore. Since the temperature of most reservoirs will be above the critical temperature of carbon dioxide, 87.8° F., the liquid carbon dioxide will, in most instances, quickly pass from the liquefied to the gaseous state upon rejection. While the injection pressure for the carbon dioxide is not particularly critical, it is preferred that it be at a value which will cause the specific volume of the carbon dioxide to range from 0.8 to 10.0 cubic feet per pound mol at reservoir temperature. The injected carbon dioxide is driven through the formation into contact with the oil which is to be displaced. The carbon dioxide is highly soluble in reservoir fluids and is generally much more soluble in oil than in water. Due to its solubility in oil, when the carbon dioxide contacts the reservoir oil a portion of it goes into solution with the reservoir oil, resulting in a viscosity reduction of the oil. In addition to the viscosity reduction, there is a preferential extraction from the oil by the carbon dioxide of light intermediate hydrocarbons containing from 2 to 5 carbon atoms, thereby developing an intermediate-rich carbon dioxide bank in the vicinity of the line of contact between the reservoir oil and the carbon dioxide. Depending upon the composition of the reservoir fluids, particularly as to amount of intermediates, and under proper conditions of temperature and pressure, the intermediate-rich carbon dioxide bank may be completely miscible with the reservoir oil. Further, there is a swelling of the reservoir oil by virtue of the dissolving of the carbon dioxide in it. The carbon dioxide should be injected in an amount which provides a transition zone of flowing fluid from the reservior oil to the displacing liquid hydrocarbon slug. Such a transition zone includes a portion next to the reservoir oil which is a carbon dioxide-reservoir oil mixture. Next is flowing carbon dioxide in phase equilibrium with any nonflowing oil in which carbon dioxide is dissolved, followed by a carbon dioxide-liquid hydrocarbon mixture adjacent to the pure liquid hydrocarbon slug. The region of flow of primarily carbon dioxide phase need be no more than a trace since the basic objective is to provide a smooth viscosity transition from the reservoir oil to the liquid hydrocarbon displacing material. The approximate quantity of carbon dioxide required may be determined by known procedures in laboratory-conducted floods under simulated reservoir conditions. The amount will, of course, be affected by reservoir conditions of temperature and pressure, together with the reservoir fluids' characteristics.

The second step of the invention involves introducing a liquefied hydrocarbon material into the formation through the injection well behind the carbon dioxide of step 1. The term "liquefied hydrocarbons" as used herein is intended to include such condensable hydrocarbons as liquefied petroleum gas, propane, butane, and light naphthas which under normal conditions of temperature and pressure exist as a liquid. The condensable hydrocarbons, of course, are introduced and maintained at a pressure which will retain them in the liquefied state. The liquefied hydrocarbons are driven into contact with the carbon dioxide with which they have a high mutual solubility. The solution of carbon dioxide and liquefied hydrocarbons thus formed provides a transition from the carbon dioxide to the liquefied hydrocarbons as discussed above. The gradual blending from the reservoir oil through to the liquefied hydrocarbon slug minimizes the fingering effect normally found in connection with the use of liquefied hydrocarbon slugs as a displacing material with the fingering being the result of decided differences in viscosity between the reservoir oil and the liquefied hydrocarbon slug. Due to the improvement of the sweep efficiency of the liquefied hydrocarbon slug effected by the carbon dioxide injected in advance of it, along with the swelling of the reservoir oil by the carbon dioxide, the quantity of liquefied hydrocarbons necessary to effectively displace the reservoir oil is significantly reduced below normal requirements.

Subsequent to the injection of the liquefied hydrocarbons, there is injected into the formation through the injection well a driving fluid which functions to displace the reservoir oil, the carbon dioxide, and the liquefied hydrocarbons through the formation to a production well, through which they are driven to the surface. The driving fluid preferably is a dry hydrocarbon gas, such as a separator gas, consisting in major part of methane with minor amounts of ethane and trace amounts of higher-boiling hydrocarbons. The driving fluid may, however, be a flue gas or air. In some cases it may be desirable to drive the injected liquefied hydrocarbons with an amphipathic liquid followed by water. An amphipathic liquid is a material having a mutual solubility with water and a hydrocarbon fluid, such as an alcohol of three or four carbon atoms and an aldehyde or a ketone. Injection of the driving fluid is continued to effect displacement of the reservoir oil through the production well until either all of the oil has been displaced from the formation or until the economical limit of the ratio of the driving fluid to reservoir oil has been reached.

While the previously described steps of the method of the invention have been discussed in the sense of their being applied through a single injection and a single production well, it is to be understood that such method is applicable to all of the various known well patterns which might be employed, such as the 5-spot system of well location.

What is claimed is:

1. In a method of recovering oil from a subterranean reservoir penetrated by at least one injection well and one production well, said wells being spaced apart one from the other, the steps which comprise:

(a) introducing carbon dioxide into said reservoir through said injection well, and driving said carbon dioxide through said reservoir, into contact with said oil, said carbon dioxide being introduced into said reservoir in an amount to provide within said reservoir a first transition zone, said first transition zone including a portion next to said oil which is a mixture of said carbon dioxide and said oil, and a carbon dioxide phase following said mixture of said carbon dioxide and said oil;

(b) introducing a liquefied hydrocarbon material into said reservoir through said injection well, and driving said liquefied hydrocarbon material through said reservoir, behind and into contact with said carbon dioxide phase, said liquefied hydrocarbon material being introduced into said reservoir at a pressure which will maintain said liquefied hydrocarbon material in the liquefied state in said reservoir to provide within said reservoir next to said carbon dioxide phase a second transition zone, said second transition zone including a portion which is a mixture of said carbon dioxide and said liquefied hydrocarbon material, and a zone of said liquefied hydrocarbon material whereby said first transition zone, said carbon dioxide phase, and said second transition zone provide a smooth viscosity transition from said oil to said zone of liquefied hydrocarbon material;

(c) introducing into said reservoir through said injection well a driving fluid to displace said oil, said transition zones, said carbon dioxide phase, and said liquefied hydrocarbon material through said reservoir toward said production well; and

(d) producing said oil from said reservoir through said production well.

2. A method in accordance with claim **1** wherein said carbon dioxide is introduced into said injection well in the liquefied state.

3. A method in accordance with claim **1** wherein said carbon dioxide is injected at a pressure which will cause the specific volume of said carbon dioxide to range from 0.8 to 10.0 cubic feet per pound mol at reservoir temperature.

4. A method in accordance with claim **1** wherein said driving fluid in step (c) is a dry hydrocarbon gas consisting in major part of methane.

5. A method in accordance with claim **1** wherein said driving fluid in step (c) is an amphipathic liquid followed by water.

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