166-308

Aug. 2, 1966 O. M. KIEL ET AL 3,263,751

PROCESS FOR INCREASING OIL RECOVERY BY MISCIBLE DISPLACEMENT

Filed Feb. 17, 1964

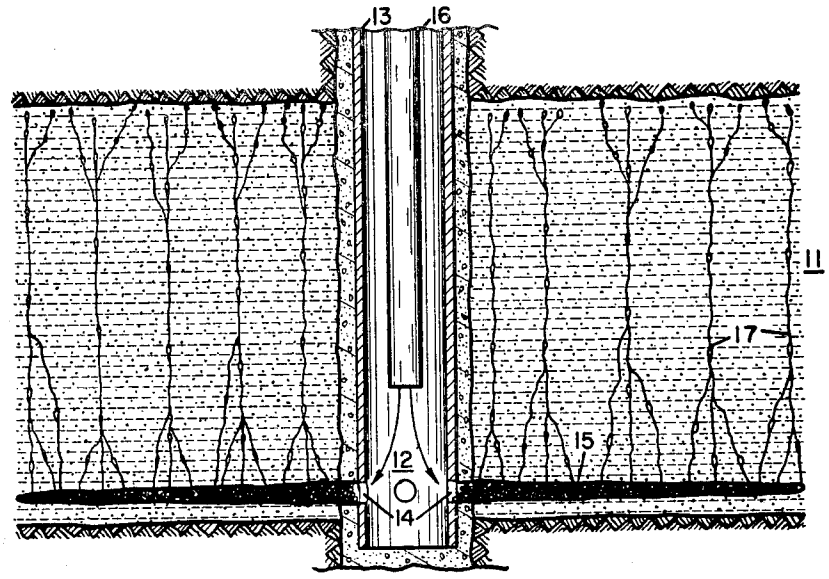


FIG. 1

1034
X 1077

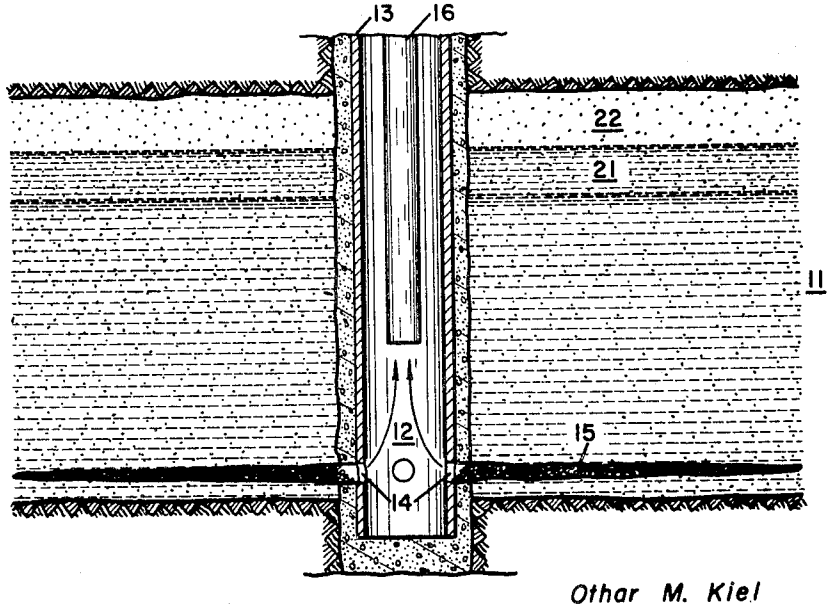


FIG. 2

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United States Patent Office 3,263,751 Patented August 2, 1966

3,263,751

PROCESS FOR INCREASING OIL RECOVERY BY MISCIBLE DISPLACEMENT

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Filed Feb. 17, 1964, Ser. No. 345,256
7 Claims. (Cl. 166—42)

This invention relates to the recovery of petroleum from subsurface reservoirs. An improved miscible displacement method is provided which involves a linear, gas-driven, gravity controlled flow mechanism. Specifically, a vertical displacement of reservoir oil is obtained by forming a horizontally oriented, propped hydraulic fracture along the lower boundary of the reservoir, then injecting condensible and relatively non-condensible gases through the fracture, in a critical sequence, followed by downward displacement and production of oil through the same fracture.

The process of the present invention is primarily applicable in the recovery of petroleum from "low energy" reservoirs. Such reservoirs include those which nature has not provided with a sufficient pressure mechanism for forcing petroleum to the surface, as well as those reservoirs which have been partially depleted by natural flow, or by other methods of so-called primary production.

A great many processes have been proposed in recent years for the secondary recovery of petroleum, some of which involve miscible fluid displacement. Such processes have enjoyed only limited success, however, for a number of reasons. Generally, such a displacement process is conducted as a "pattern flood" in which a bank of miscible fluid is introduced at one or more injection wells, and is driven by radial flow toward one or more production wells where the displaced hydrocarbons are lifted to the surface of the earth. The limited success of a miscible pattern flood is caused partly by the inherent character of a radial flow system. Since a high pressure drop is observed at each injection well, satisfactory injection rates are seldom obtained. Moreover, pressure gradients differ greatly from place to place within the reservoir, such that oily cannot be uniformly displaced, even from an "ideal" system.

Another factor which is commonly recognized as severely limiting the efficiency of such pattern floods is gravity segregation. The density of reservoir oils is usually greater than the density of the miscible fluids used for displacement drives. Because of this density difference, gravity causes the miscible fluid to migrate upward in the reservoir, causing poor conformance. Another major reason for the low efficiency of such processes is the difference in viscosity between the reservoir oil and most displacing fluids. An unfavorable viscosity ratio, or "mobility ratio," causes excessive fingering and channeling of the miscible bank through the reservoir, thus bypassing large volumes of reservoir oil, which further reduces the efficiency of the process.

It is an object of the present invention not only to avoid the inherent shortcomings of a radial system, by substituting linear flow, but also to provide vertical downward displacement whereby gravity acts in opposition to the fingering tendency caused by a high mobility ratio. It is a unique feature of the invention that a single fracture is utilized to avoid the disadvantages normally associated with both radial injection flow and radial production flow.

In accordance with the present invention a borehole is drilled substantially completely through the oil-bearing interval to be produced. Preferably, casing is cemented throughout the oil-bearing interval, although an open-hole completion can be employed. The well is perforated

only at or near the lower boundary of the pay zone. The formation is then hydraulically fractured at the perforated level. The fracture must be horizontally oriented and have a relatively large areal extent. By "horizontally oriented" it is intended, specifically, that the fracture is propagated along the natural orientation of the bedding planes at the perforated level. Typically, this orientation is substantially horizontal. The fracture is propped with sand or other propping agent in order to ensure the maintenance of high fluid conductivity throughout the productive life of the reservoir.

In most cases it is preferred to locate the fracture substantially at or just above the lower boundary of the oil-bearing zone, since only that portion of the reservoir which lies above the fracture is subjected to efficient displacement. However, it is wholly feasible and perhaps desirable in certain instances to locate the fracture a considerable distance above the lower boundary of the oil-bearing zone. For example, in some reservoirs a shale streak or other permeability barrier will be found to prevent exploitation of the full thickness surrounding one or more wells. In such cases, the fracture is located just above the barrier.

Once the fracture is established the well is flushed free of fracturing fluid and pumped down to release any residual formation pressure. A gaseous fluid, capable of condensing at some pressure below fracturing pressure to form an oil-miscible liquid, is then injected through the fracture and into the formation. Propane is the preferred injection fluid at this stage of the operation. Other suitable gases capable of condensing at moderately elevated pressures to form a liquid phase at least partially miscible with the reservoir oil include, for example, ethane and carbon dioxide. The injection of propane gas is continued at a controlled pressure to avoid premature condensation. As a result the propane rapidly fills the fracture volume, with only a small pressure drop, and is driven vertically toward the upper boundary of the oil-bearing zone, where it collects under gradually increasing pressures. This upward flow of the propane is favored not only by the forces of density difference between the gas and the reservoir hydrocarbons, but also because of the high mobility of the gaseous phase relative to that of the reservoir oil.

After a sufficient volume of propane is injected, the injection of methane or other relatively immiscible gas is commenced. Preferably, the gas which follows the propane is substantially immiscible with the reservoir oil at the pressure of injection, but miscible with propane. The methane or other gas penetrates substantially uniformly throughout the fracture volume, as did the propane, and is readily driven upward through the reservoir because of its high mobility, its low density, and the compressibility of the injected propane. Initially, the methane approaches the upper boundary of the oil-bearing formation where it collects at substantially the same level as the previously injected volumes of propane. The continued injection of methane raises the reservoir pressure above the vapor pressure of propane, at reservoir temperatures, thereby forcing a substantial condensation of propane. The condensed propane forms a uniformly distributed miscible layer between the methane and the reservoir oil. The heat released by condensation of the propane is effective in reducing the viscosity, and increasing the mobility of reservoir oil. The injection of methane is continued until the condensed propane layer fills at least 1.0% of the pore space of the formation, and preferably from 3 to 10%. A portion of the methane is absorbed by the condensed propane, while the remainder readily fingers through the propane-methane layer and continues to collect at the uppermost level of the reservoir. The injection of methane is continued until the reservoir pressure is raised to at least 20 p.s.i., and

preferably at least 50 p.s.i., above the vapor pressure of the propane or its equivalent.

The well is then opened for production of reservoir oil. As the oil is produced at a controlled rate, the miscible propane layer is forced gradually downward by the expanding methane. Back pressure is held on the well to control the withdrawal rate, so that gravity segregation can limit or off-set the tendency of propane to finger through the reservoir oil. In this manner the miscible propane front moves (linearly) downwardly to the fracture plane, miscibly displacing reservoir oil as it moves. For relatively thin formations, a single stage of propane and methane injection can raise the reservoir pressure to a point which will permit the production of substantially all the reservoir oil. For thicker formations, one or more additional cycles of methane injection, followed by continued production, are carried out until substantially all the reservoir is subjected to miscible displacement.

Ultimately, the injected gases are readily recoverable, at exceptionally high rates, again because of the inherent advantage of vertical linear flow into a horizontal fracture of large areal extent, compared with radial flow.

It has been known for several years that the hydraulic fracturing of a relatively shallow reservoir can readily produce a fracture having substantially horizontal orientation. Horizontal orientation, rather than vertical, is relatively certain up to a depth of about 2,000 feet. At greater depths, up to about 2,500 feet, horizontal orientation is common, yet not certain. At depths in excess of 2,500 feet, a fracture may be either horizontal or vertical, with the vertical orientation predominating at progressively increasing depths. Conventional techniques of forming and propping horizontally oriented hydraulic fractures are well known in the art and need not be described in further detail for the purposes of this disclosure. A detailed description of such fracturing techniques may be found in the Journal of Petroleum Technology, vol. XIII, No. 4, pp. 371–376 (April 1961).

A sequential injection of the condensible gas, followed by the non-condensible gas, is an essential feature of the present invention. A reversed sequence, methane followed by propane, would be unsuccessful since the increase in reservoir pressure due to methane injection would, subsequently, cause immediate condensation of propane gas, before the latter would be able to pass into the reservoir. Premature condensation of the propane would be highly detrimental, since the mobility of liquid propane, although greater than that of reservoir oil, is much less than that of the gaseous phase. Consequently, the propane would become distributed throughout the lower portion of the reservoir, as opposed to uniform collection near the upper boundary of the oil-bearing zone, as desired.

Injection of propane-methane mixtures is also undesirable for essentially the same reason. That is, the reservoir pressure would be raised too rapidly thereby permitting only the initial volumes of propane to reach the upper boundary of the oil-bearing zone prior to condensation. A premature condensation would again result to a substantial degree, causing an adverse distribution of propane, as opposed to its collection at a discrete level near the upper boundary of the reservoir.

In accordance with a preferred embodiment of the invention, the injected propane gas is followed by gaseous ethane, which is then followed by methane or natural gas. The ethane provides improved miscibility between the condensed-gas phase and the methane, especially at lower pressures. It also provides additional condensed phase, and can be injected at higher pressures than propane without danger of premature condensation. In this embodiment, the injection of ethane gas sweeps the propane efficiently upward, to form a layer comprising ethane and propane near the upper boundary. The volume of ethane should be sufficient to provide at least 0.1% pore volume

of liquid phase, and preferably at least 1.0%. Ultimately, as before, methane or natural gas is injected whereby the remaining ethane is swept upward as the reservoir pressure is progressively increased. Injection of natural gas is then continued until substantially the entire volume of injected propane is condensed. In addition, a substantial proportion of the ethane is condensed, and a portion of the methane is absorbed, to supplement the volume of the miscible liquid layer.

FIGURE 1 illustrates the injection stage or stages of the process.

FIGURE 2 shows the oil-producing stage of the process.

In FIGURE 1 oil-bearing formation **11** is penetrated by borehole **12** extending therethrough. Casing **13** is cemented throughout the oil-bearing interval and is provided with perforations **14** only at or near the bottom of the oil-bearing formation.

A large, horizontally oriented, hydraulic fracture **15** is propagated at the level of perforations **14** to a radial distance of at least 50 feet from the wellbore, and preferably from 100 to 500 ft. The fracture is filled with sand or other propping agent, to ensure high conductivity. Once the fracture is established the well is flushed free of fracturing fluid and, preferably, is pumped down to permit the escape of any gas pressure initially present. In some reservoirs, an appreciable volume of oil can readily be produced at this stage, although as stated earlier, the invention is primarily intended for application to low energy reservoirs. If the oil saturation is high, say 60% of the pore volume or greater, then the additional withdrawal of even a small proportion of the oil is desirable, since the permeability to gas will be increased, thereby reducing the power requirement for propane and methane injection.

The injection of propane or other condensible gas is then begun via tubing **16** and/or casing **13**. The conductivity of fracture **15** must be at least 200 millidarcy feet, and preferably 500 to 2000 millidarcy feet. This conductivity is so great, relative to the remainder of the formation, that the entire fracture is subjected to substantially the same injection pressure. The injection pressure is maintained below the vapor pressure of propane, at reservoir temperature, in order to avoid any significant amount of premature condensation. The injected gas fingers rapidly upward, as indicated by multiple flow paths **17**. A sufficient volume of propane is injected to provide, after condensation, a liquid phase which fills at least 1.0% of the reservoir pore volume, and preferably at least 3% thereof. The propane is followed by the injection of methane, or other relatively non-condensible gas, which also fingers rapidly upward through the formation, sweeping the last increments of injected propane together therewith, as it rises to the upper boundary of the oil-bearing zone.

In FIGURE 2, once sufficient methane is injected to raise the reservoir pressure substantially above the vapor pressure of propane, a condensed layer of liquid propane **21** is formed, which absorbs a substantial volume of methane. Methane bank **22** forms at the uppermost level of the reservoir, since the propane-methane layer becomes saturated with methane, thereby permitting subsequently injected methane to finger readily through the liquid layer. A sufficient volume of methane is injected to raise the reservoir pressure to a level at least about 50 p.s.i. greater than the vapor pressure of propane, and preferably from two to eight times the vapor pressure of propane. Only by generating such excess pressure in the reservoir can the subsequent downward migration of the propane bank proceed without excessive shrinkage. Stated otherwise, the reservoir pressure during the producing stage of the process cannot be allowed to drop below the vapor pressure of propane, since this would permit excessive evaporation and consequent reduction in size of the propane bank, thereby sacrificing the essen-

tial miscible nature of the displacement. Accordingly, in the event that reservoir pressure does drop near the vapor pressure of propane, production is discontinued and the injection of methane or its equivalent, alone or in combination with ethane, is resumed until the reservoir pressure is again raised substantially above the vapor pressure of propane. Thereafter the well is again opened for continued production of reservoir oil. It may be necessary in very thick reservoirs to repeat the injection and production cycles three or more times in order to substantially deplete the reservoir.

As a specific example of the invention, the method is applied to a reservoir having the following characteristics:

Thickness	feet	30
Permeability	millidarcies	20
Porosity		0.20
Temperature	° F.	80
Oil saturation	pore volume	0.50
Oil gravity	° A.P.I.	30
Oil viscosity	centipoises	6.0
Gas saturation	pore volume	0.20
Gas viscosity	centipoises	0.012
Connate water	pore volume	0.30

Casing is set and cemented in a wellbore penetrating the full thickness of the reservoir. The well is then perforated only at the lower boundary of the oil-bearing zone. A hydraulic fracture is propagated horizontally from the wellbore at the perforated level. The fracture is determined to have an average radius of about 370 ft., and is propped with sand to provide a flow capacity of about 1,670 millidarcy feet. Each well of the reservoir, with 10 acre spacing, can be similarly completed and fractured.

Propane gas is then injected through each well at a rate of about 900,000 s.c.f. per day for 37 days, which raises the reservoir pressure to about 140 p.s.i. Methane, or natural gas, is then injected for 73 days at the same rate, which raises the reservoir to about 500 p.s.i., and provides a miscible condensed phase near the top of the reservoir, filling about 5% of the total pore volume.

Production of oil is then begun. Calculations show that a withdrawal rate of about 85 barrels per day from each well can be maintained without causing a significant amount of propane to finger downward through the reservoir. At this rate 85% of the oil is recoverable in 6.4 years.

In this particular example, a withdrawal rate of 85 barrels per day corresponds to a vertical pressure gradient in the reservoir of about 0.01 p.s.i. per foot. In general, a vertical pressure gradient of up to 0.1 p.s.i. per foot can be employed without failure due to excessive fingering. In very thick reservoirs a greater pressure gradient can be employed, up to about 0.3 p.s.i. per foot, since increased fingering can then be tolerated. Preferably, a gradient of 0.005 to 0.05 p.s.i. per foot is employed.

What is claimed is:

1. A process for the recovery of petroleum from a subsurface reservoir which comprises drilling a wellbore through substantially the entire oil-bearing zone, limiting communication between said zone and said wellbore to substantially the lower boundary level thereof, forming a highly conductive, horizontally oriented fracture at said level of communication, injecting through said fracture and into the reservoir a condensible gas, the liquid phase of which exhibits a substantial degree of miscibility with the reservoir oil, thereafter injecting a relatively non-condensible gas through said fracture and into the reservoir, the volume of said non-condensible gas being sufficient to raise the reservoir pressure at least 50 p.s.i. above the vapor pressure of the condensible gas, discontinuing injection of said non-condensible gas and thereafter producing oil from said reservoir through said fracture, with a controlled back pressure sufficient to permit the effects of gravity segregation to balance the tendency for the condensed layer of miscible liquid to finger through the reservoir oil.

2. A process as defined by claim 1 further comprising the steps of discontinuing the production of oil from said reservoir when reservoir pressure drops to about the vapor pressure of said condensible gas, then injecting additional non-condensible gas, and thereafter resuming production of oil.

3. A method of recovering petroleum from a subterranean reservoir penetrated by a wellbore and having substantial vertical permeability, which comprises forming a horizontally oriented, highly conductive, propped hydraulic fracture of relatively large areal extent near the lower boundary of the reservoir, injecting a first gas through said fracture and into the reservoir, said first gas being condensible to form an oil-miscible liquid phase at a pressure substantially below the pressure required to fracture the reservoir, the volume of said first gas being sufficient to provide at least 3% pore volume of condensate, then injecting a relatively non-condensible gas through said fracture and into said reservoir, the volume of said non-condensible gas being sufficient to raise the reservoir pressure above the vapor pressure of said first gas at reservoir temperature, thereafter reversing flow in said wellbore to produce oil from the reservoir, whereby a condensed layer of said first gas miscibly displaces the oil vertically downward, and is driven by expansion of said non-condensible gas.

4. A method of recovering petroleum from a subsurface reservoir having a depth not greater than 2500 feet, which comprises drilling a borehole into said reservoir a substantial distance below the upper boundary thereof, forming a substantially horizontally oriented, highly conductive, propped hydraulic fracture extending radially into said reservoir from said borehole, at a depth substantially below the upper boundary of said reservoir, then injecting an amount of gaseous propane into the reservoir through said fracture, sufficient to provide at least 3% pore volume of liquid propane, then introducing a volume of methane-comprising gas into the reservoir through said fracture, sufficient to raise the reservoir pressure substantially higher than the vapor pressure of propane, discontinuing injection, and then producing reservoir oil through said fracture and into the wellbore, whereby a miscible layer of propane is formed and is driven vertically downward by expansion of accumulated methane-comprising gas near the upper boundary of said reservoir.

5. A method as defined by claim 4, further comprising the step of controlling the rate of oil production to provide a vertical pressure gradient no greater than 0.05 p.s.i. per foot.

6. A method of recovering petroleum from a subsurface reservoir having a depth not greater than about 2500 feet, which comprises drilling a borehole into said reservoir a substantial distance below the upper boundary thereof, forming a substantially horizontally oriented, highly conductive, propped hydraulic fracture extending radially into said reservoir from said borehole, at a depth substantially below the upper boundary of said reservoir, then injecting an amount of gaseous propane into the reservoir through said fracture, sufficient to provide at least 3% pore volume of liquid propane, then injecting a volume of ethane-comprising gas into the reservoir through said fracture, sufficient to provide at least 0.1% pore volume of liquid ethane, then introducing a volume of methane-comprising gas into the reservoir through said fracture, sufficient to raise the reservoir pressure substantially above the vapor pressure of propane, discontinuing injection, and then producing reservoir oil through said fracture and into the well bore, whereby a miscible layer containing propane and ethane is formed and is driven vertically downward by expansion of accumulated methane-comprising gas along the upper boundary of said reservoir.

7. A method as defined by claim 6 wherein the rate of oil production is controlled to provide a vertical pressure gradient within the reservoir of no more than 0.05 p.s.i. per foot.

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