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# METHOD FOR CONSOLIDATING UNCONSOLIDATED SUBSURFACE FORMATIONS

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This invention relates to a method of treating unconsolidated subsurface formations, and more particularly to a method of bonding particles of such formations into a permeable unitary mass to prevent movement of the particles into the borehole of a well penetrating the unconsolidated formation.

Many subsurface formations from which oil or gas is produced are unconsolidated formations in which the individual sand particles of the formation are weakly bonded to one another. When formation fluids are produced from such formations, sand particles are carried by the fluids into the borehole of the well where they may plug the well or production tubing and prevent production of oil from the well. If the oil-bearing formation is under a high pressure, the sand carried into the well frequently flows at a high velocity through borehole equipment and causes serious erosion of the equipment. Both plugging and erosion of the well equipment make expensive shutdown and workover of the well necessary to allow further production from the well.

Several methods have been used to combat the flow of sands into the well from unconsolidated formations. One of the techniques is to install a slotted liner in the borehole of the well through the pay zone. The slots of the liner are narrow enough to prevent flow of sand through them. Slotted liners frequently fail to accomplish the desired purpose because the movement of the sand around the liner may block the passages in the liner and prevent flow into the well.

Another technique that is employed is to pack fine gravel around a liner to produce a filter bed with small openings through which the sand particles cannot move. The gravel packing technique has the advantage of providing some support to the unconsolidated formation, but suffers the same disadvantage as the unconsolidated formation that the sand particles are not bonded together and may move to plug passages through which oil flows into the well.

It has also been suggested that the particles in the gravel pack be treated by displacing a resin-forming liquid into the gravel pack to coat the particles and thereafter setting the resin-forming liquid by condensation or polymerization to bond the particles into a unitary mass. Care must be taken to insure preservation of the permeability of the formation after the resin treatment. One of the difficulties with such a method is finding a suitable resin which can be made to set at conditions existing in the pay zone to form a resin of adequate strength and insolubility in formation fluids to produce a bond which will hold the particles together for long periods. Another problem encountered in forming a mass of adequate strength is in obtaining satisfactory adhesion of the resin to the particles which are ordinarily covered with oil and water, or both, when the resin-forming liquid is displaced through the gravel pack. Still another difficulty in consolidating formations by means of resins is that the injected resin-forming liquid tends to finger its way through the formation; hence leaves substantial areas untreated. Because of these difficulties, and the relatively high cost of the large amount of resin required, the use of resins to consolidate formations has not been widely adopted.

Another method that has been used to consolidate incompetent formations is to pass hot gases through an incompetent formation containing a cokable oil to deposit coke which bonds the particles into a strong mass. The passage of gas through the formation while the coke is being formed insures permeability of the consolidated formation. If the gases are inert, such as nitrogen or flue gases, they should be of a relatively high temperature, for example, 600° to 1000° F., or higher, to convert the heavy residual fractions of the oil into coke. It is essential that the oxygen concentration be kept very low, for example, less than one percent in the hot inert gases to avoid ignition of oil in the formation and combustion of the coke. Oxygen-free inert gas is usually not available at the well head, but even if available, ordinarily requires a down-hole electric heater to heat the inert gas to the desired temperature.



Coke can also be deposited by passing an oxygen-containing gas through the formation surrounding the borehole of a well, and that procedure has advantages over the use of hot inert gases because of the lower solubility in oil and higher physical strength of the resultant coke. However, injection of hot air or of air mixed with combustion products into an oil-bearing formation requires very careful control of the temperature at which the air is injected into the formation to prevent ignition of the oil and combustion of the coke deposited in the formation. Moreover, difficulty has been experienced during attempts to consolidate a long exposed interval of an incompetent formation by the injection of hot oxygen-containing gases because of a tendency of the injected oxygen-containing gases to channel into the formation, presumably in upper strata, and allow oil to flow into the borehole, presumably from strata in the lower part of the formation. Oil then becomes ignited in the borehole which prevents the necessary careful control of the temperature of the gases injected into the formation.

This invention resides in a method of consolidating an incompetent formation penetrated by a well in which steam and air are mixed at conditions and in proportions causing a portion of the steam to condense, and the resulting mixture is displaced down a well and into the incompetent formation. Injection of the mixture of steam, condensed steam, hereinafter referred to as "condensate," and air into the formation is continued for a period adequate to bond the incompetent formation with coke for a desired distance from the borehole wall. Consolidation of the formation in accordance with this invention is particularly useful in consolidating long exposed intervals of the borehole.

It has been found that a mixture of steam, condensate, and air can be injected directly into an incompetent subsurface formation containing a cokable oil at high temperatures to deposit coke in the formation and thereby bond the particles of the formation into a mass of adequate strength to withstand the erosive forces resulting from production of oil. When steam is mixed with the air under conditions causing condensation of a part of the steam, ignition of coke deposited in the formation does not occur even though the injected mixture is at temperatures which consistently ignite and burn all of the coke when the air injection is in the absence of steam and condensate. The mixture of steam, condensate, and air can be injected at temperatures of approximately 200° to 500° F., preferably temperatures of 250° to 400° F. and still more desirably temperatures in the range of 300° to 400° F., to produce a coke insoluble in oil and having adequate strength to prevent flow of sand into the well. A gaseous mixture suitable for consolidating an incompetent formation in accordance with this invention can readily be prepared by mixing saturated steam and cold air in substantially any proportions resulting in a gaseous mixture containing more than one percent free oxygen.

The term "cold air" means air at a temperature lower than the temperature of the saturated steam with which it is mixed. The cold air mixed with the steam will ordinarily be at the temperature at which it is discharged from the compressor, and is usually less than 200° F. It is preferred that the ratio, by weight, of steam to air be in the range from 3:1 to 1:10. Air can also be mixed with superheated steam to provide the desired mixture for injection into the incompetent formation, but if superheated steam is used, the ratio of steam to air and the temperature of the air introduced into the mixture must be such as to cause condensation of a portion of the steam when the two gases are mixed.

The mixture of steam, condensate, and air is displaced from the well into the incompetent formation at an air flux less than 500 std. cu. ft./sq. ft./hr. and preferably in the range of 5 to 100 std. cu. ft./sq. ft./hr. for a period of at least 8 hours The pressure at which the mixture is injected is controlled to give an air flux in the desired range. Ordinarily it is desirable to continue the injection of the steam-condensate-air mixture for 24 to 48 hours to insure the deposition of coke for an adequate distance from the borehole wall. Longer periods of injection of the steam-condensate-air mixture can be employed if desired without destroying the coke deposited adjacent the borehole wall. The time and temperature necessary for the deposition of the coke can be determined by suitable laboratory tests on cores of the formation containing oil derived from the formation.

Although this invention is not restricted to a particular theory, it is believed that the air displaced into the formation reacts with oil in the oil-bearing formation to form oil-insoluble oxygenated products with the attendant liberation of heat. The resultant increase in temperature serves both to increase the rate of oxidation and cause polymerization of heavy residual hydrocarbons to deposit coke in the formation and results in a zone of peak temperature at some location radially outward from the borehole wall. Whether or not ignition of oil in the formation occurs will depend on the relative rates of liberation of heat in the oxidation zone and removal of heat from that zone by conduction to the formation, convection of hot gases radially outward into the surrounding formation, and the vaporization of water carried into the formation with the injected oxygen-containing gas. Because the rate of the oxidation reaction, particularly at high temperatures, may be limited by the amount of air available for reaction, and the heat lost by conduction to the surrounding formation may be large, those factors will limit the maximum temperature in the oxidation zone. Maintenance of the air flux below 500 std. cu. ft./sq. ft./hr. may prevent liberation of heat at a rate faster than the heat can be safely carried away by conduction to the surrounding formation and convection. The cooling effect resulting from the evaporation of the condensate occurs primarily between the peak temperature zone and the borehole wall. Hence, even though combustion does occur at the peak temperature zone, and field tests have shown that combustion at some location in the formation does occur, the mixture of steam, condensate, and air is effective in preventing reverse combustion travelling from the zone of peak temperature to the borehole. Regardless of the mechanism, it has been found that incompetent oil-bearing formations can be effectively consolidated by the injection of a mixture of steam, condensate, and air into a well and displacement of the fluids down the well and into the incompetent formation, as is shown by the following examples.

A well was drilled into the Yorba Linda field and a slotted liner 238 feet long was set in the well through the productive interval at a depth of 355 to 555 feet. Sand flowed into the well as oil was produced, necessitating shutting down the well and reworking the well to rid it of sand. Saturated steam at a surface pressure



of 102 pounds per square inch gauge was injected into the well at a rate of 34,000 pounds of steam per day. Air was injected into the upper end of the well simultaneosuly with the steam and displaced down the well at a rate of 765,000 cu. ft. per day. The bottom hole temperature was 270° F. The injection of the mixture of steam and air was continued for 24 hours during which the surface pressure was increased to 210 pounds per square inch gauge. The rate of injection of saturated steam was increased to 72,500 pounds per day and the rate of air injection was increased to 790,000 cu. ft. per day. Injection of the steam and air into the well at the higher rates continued for 24 hours. During both 24-hour periods the air was at the temperature, in the range of 80°–100° F., at which it was discharged from the compressor. Mixing of the saturated steam and air caused a portion of the steam to condense. The well was then placed on production with no difficulty with the production of sand. Table I illustrates the performance of the well before and after consolidation of the formation.

TABLE I.—SAND PRODUCTION FROM WELL COMPLETED WITH SLOTTED LINER—238 FT. LONG—BEFORE AND AFTER STEAM-CONDENSATE-AIR COKING

| Months After Coking | Avg. Oil Production (B.P.D.) | Sand Prod. (Bbls.) | Cumulative Sand (Bbls.) | Remarks |
|---|---|---|---|---|
| −2 | 60 | 2 | 2 | Well sanded up twice. Sporadic oil production. |
| −1 | 50 | 2 | 4 | Well sanded up twice. Injected 195,000 lbs. steam. |
| 0 | ---------- | 0 | 4 | Injected steam and air for 2 days. |
| 1 | 50 | 0 | ---------- | |
| 2 | 50 | 0 | ---------- | Injected air for 1 week. |
| 3 | 40 | 0 | ---------- | |
| 4 | 10 | 1 | 5 | |
| 5 | 45 | 0 | 5 | Injected air for 1 week. |

The single barrel of sand produced during the fourth month after coking is not an indication of sand production, but is believed to be the result of a gradual accumulation that happened to be cleaned out during that month.

In a second well in the Yorba Linda field, the procedure described above was repeated, with the exception that the steam-air ratios were lower and the injection of the steam and air mixture was continued over a period of five days. A slotted liner 210 feet long was set in the well opposite the oil-bearing formation which had a maximum depth of 650 feet. The schedule of mixing saturated steam and air for injection during the five days is set forth in the following Table II.

TABLE II

| | Bottom Hole Injection Temp., ° F. | Saturated Steam Pressure, p.s.i.g. at Surface | Steam, Pounds/Day | Air, Mcf/Day |
|---|---|---|---|---|
| 1 | 140 | 187 | 11,000 | 680 |
| 2 | 235 | 215 | 10,000 | 738 |
| 3 | 250 | 207 | 12,300 | 462 |
| 4 | 200 | 222 | 23,600 | 764 |
| 5 | 218 | 225 | 13,000 | 780 |

Before the treatment of the well in accordance with the schedule set forth in Table II, the well produced sand. Following the injection of the steam-condensate-air mixture into the incompetent formation, the well was placed on production with no movement of sand into the well. Moreover, subsequent injection of steam into the well for a five-day period to stimulate production did not result in the production of sand when the well was returned to production.

Attempts have been made to consolidate the borehole wall of wells in the Yorba Linda field by the injection of steam alone. In spite of the injection of steam over a period of 8 days, 2 days, and 2 days, in a series of tests no consolidation of the incompetent formation was obtained. Repeated efforts to consolidate the borehole wall by the injection of air heated by a downhole burner resulted in fires in the borehole of the well even though the temperature of the air and combustion products was as low as 200° F. Apparently oil flowed into the borehole of the well and was oxidized, thereby raising the temperature in the borehole to a level causing combustion of oil in the formation and preventing consolidation of the formation.

It is an important advantage of the process of this invention that it permit the use of a low air flux in the coking operation without danger of causing ignition of oil in the formation adjacent the borehole. The injection of warm air either alone or mixed with combustion products to cause the formation to coke requires high injection rates and careful temperature control to prevent ignition and burning of the coke deposited in the formation. The higher injection rates, while effective when the coking is to be performed adjacent a notch or perforations, would require excessive compressor capacity to consolidate a long interval of exposed formation such as that which was successfully treated by the method of this invention in the Yorba Linda field.

Condensation of a portion of the steam upon admixture with air is important to the consolidation of an incompetent formation containing a heavy oil by the process of this invention. Attempts to consolidate a formation by the injection of hot air with the concurrent delivery of a stream of water into the well have not been successful in producing the desired bonding of the formation. Moreover, combustion tube tests have shown a dry mixture of superheated steam and air to be ineffective in forming coke bonding particles of sand together, probably because of removal of oil by the superheated steam or by combustion.

Injection of a mixture of steam, condensate, and air in accordance with this invention to consolidate incompetent formations is especially advantageous in coking long exposed intervals of oil-bearing formations, such as exposed intervals exceeding forty feet in length. Attempts to consolidate long intervals of exposed incompetent formations by warm air coking processes in which warm air is injected into the formation mixed with flue gases, but not in admixture with steam and condensate, have experienced difficulties with borehole fires. No such difficulties have been encountered when the consolidation is obtained by the injection of a mixture of steam, condensate, and air. This method is not, however, restricted to consolidation of long exposed intervals, but is effective in the consolidation of incompetent formations adjacent to perforations or notches in casing set through such formations to prevent movement of sand through the perforations or notches when fluids are produced from the formation. If the oil in the incompetent formation should contain insufficient heavy fractions, or the oil should be displaced from the formation adjacent the well during the drilling or completion of the well, a heavy, readily cokable oil can be injected into the formation ahead of the mixture of steam, condensate, and air.

We claim:

1. A method of consolidating an incompetent oil-bearing formation penetrated by the borehole of a well comprising injecting down the well and into said formation a mixture of steam, condensate, and air at a temperature in the range of 200° to 500° F. for a continuous period adequate to convert oil in the formation adjacent the borehole to coke bonding the particles of the incompetent formation into a strong permeable mass.

2. A method of consolidating an incompetent oil-bearing formation penetrated by the borehole of a well comprising mixing steam and air to form in the borehole a mixture of steam, condensate, and air at a temperature of 200° to 500° F., and displacing said mixture from the well into said incompetent formation for a continuous period adequate to convert oil in the formation adjacent the borehole to coke bonding the particles of the incompetent formation into a strong permeable mass.

3. A method as set forth in claim 2 in which the steam mixed with the air is saturated steam.

4. A method as set forth in claim 2 in which the steam mixed with the air is superheated steam.

5. A method of consolidating an incompetent formation contiguous to the borehole of a well penetrating the formation to prevent flow of sand into the well during production of formation fluids comprising setting a slotted liner through the interval to be consolidated, mixing steam and air at conditions and in a ratio to provide in the borehole a mixture of steam, condensate, and air containing at least one percent of oxygen at a temperature of 200° to 500° F., maintaining said condensate-bearing mixture in the borehole and displacing said mixture from the well into the incompetent formation adjacent the borehole for a continuous period of at least eight hours.

6. A method of consolidating an incompetent formation penetrated by the borehole of a well comprising mixing steam and air in a ratio and under conditions to provide in the borehole a mixture of steam, condensate, and air containing at least one percent oxygen and at a temperature in the range of 200° to 500° F., maintaining said condensate-bearing mixture in the borehole and displacing said mixture from the well into the incompetent formation for a continuous period adequate to convert oil in the formation immediately surounding the borehole to coke bonding the particles of the incompetent formation into a strong permeable mass.

7. A method as set forth in claim 6 in which the condensate-bearing mixture is maintained in the borehole and displaced into the incompetent formation adjacent the borehole for a continuous period of at least 24 hours.

8. A method of consolidating an incompetent oil-bearing formation penetrated by the borehole of a well comprising displacing down the borehole a mixture of steam, condensate, and air at a temperature within the range of 200° F. to 500° F., maintaining said condensate-bearing mixture in the borehole, contacting with the mixture in the bore hole an interval of the formation having a thickness of at least about forty feet, and displacing the mixture into the formation for a continuous period adequate to convert oil and formation particles in the formation adjacent the borehole into a strong permeable mass.

9. A method of consolidating an incompetent oil bearing formation contiguous to the borehole of a well penetrating the formation comprising mixing saturated steam and air at a temperature lower than the temperature of the saturated steam to form in the borehole a mixture of steam, condensate and air at a temperature of 200° to 500° F., the ratio by weight of steam to the air with which the steam is mixed being in the range of 3:1 to 1:10, maintaining said condensate-bearing mixture in the borehole and displacing said mixture from the borehole into the incompetent formation for a continuous period adequate to convert oil in the formation adjacent the borehole to coke bonding the particles of the incompetent formation into a strong permeable mass.

10. A method for consolidating an incompetent oil-bearing formation contiguous to the borehole of a well penetrating the formation comprising mixing saturated steam and air at a temperature lower than the temperature of the saturated steam to form in the borehole a mixture of steam, condensate and air at a temperature of 250° to 400° F., the ratio by weight of steam to the air with which the steam is mixed being in the range of 3:1 to 1:10, maintaining said condensate-bearing mixture in the borehole and displacing the mixture from the borehole into the incompetent formation for a continuous period

adequate to convert oil in the formation adjacent the borehole to coke bonding the particles of the incompetent formation into a strong permeable mass.

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