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METHOD FOR CONSOLIDATING AN UNCONSOLIDATED FORMATION

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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 condition 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. One 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. 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.

This invention resides in a method for bonding unconsolidated sands into a strong, permeable, unitary mass by coking oil place in the formation surrounding the borehole of a well. In the process of this invention the coke formed in the unconsolidated formation is of high

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strength and is highly resistant to dissolution of weakening by the formation fluids. The coke is formed by the displacement of an oxygen-containing gas, preferably air, at low temperatures and at relatively high flow rates from the borehole through the unconsolidated formation, and thereafter gradually increasing the temperature of such air to a temperature at which the air reacts with the oil to form a strong coke highly insoluble in oil. The continued flow of gases through the formation during the creation of the coke bonding the particles together preserves the permeability of the bonded structure around the borehole of the well.

Although this invention is not restricted to any particular theory, it is believed that the extended contact of the oil in the formation around the borehole with air at relatively low, but gradually increasing, temperatures results in consumption of a substantial part of the capacity of oil to react with oxygen at conditions at which the reaction is slow and the heat liberated by such reaction can readily be carried away by the gasses passing through the formation. Then, when the severity of the oxidizing conditions to which the oil is exposed is increased by increasing the temperature of the oxygen-containing gas passing through the formation to a level at which a strong oil-insoluble coke is formed, the oil is not sufficiently reactive with oxygen to support reverse combustion close to the borehole of the well. In this connection, the residual hydrocarbons are the most readily oxidized hydrocarbons. Removal of volatile hydrocarbons from the formation adjacent the borehole by the injected gases of gradually increasing temperature has little effect in reducing the reactivity of the oil in the formation with oxygen.

In the process of this invention, ignition of oil in the unconsolidated formation usually occurs at some distance from the borehole after the temperature of the oxygen-containing gas injected into the formation has been raised to a level at which a strong oil-insoluble coke is formed. The combustion may initially be either forward or reverse. The term "forward burning" refers to combustion in which the direction of movement of the combustion front is the same as the direction of flow of the oxygen-containing gases. The term "reverse burning" refers to combustion in which the direction of movement of the combustion front is opposite to the direction of movement of the oxygen-containing gases.

It is a characteristic of reverse combustion in permeable oil-bearing formations that after reverse combustion has proceeded to a point at which the rate of heat liberation at the combustion front is less than the rate of heat loss, upon continued injection of an oxygen-containing gas the combustion is converted to forward burning. The forward combustion burns the coke left behind the combustion front during reverse burning and thereby destroys any bonding of the sand particles. It is the forward combustion near the borehole, which may occur directly or following reverse combustion which moves the combustion front to the vicinity of the borehole, that constitutes the detrimental combustion that must be avoided. In the process of this invention, such detrimental combustion is avoided by careful control of the temperature and flux of the oxygen-containing gas in accordance with a schedule providing for a gradual increase in the temperature of the injected gas.

The minimum permissible distance from the borehole wall to the closest combustion depends upon the thickness of the sleeve of coke-bonded formation necessary to support the formation. The strength of the formation and the pressure to which the formation is subjected are important in determining the thickness of the coke sleeve necessary to prevent movement of sand into the well. Usually, it is desirable to form a sleeve of the formation

bonded with coke at least one foot, and preferably at least two feet, in wall thickness. In some instances a thickness of as little as six inches is adequate.

In the process of this invention, an oxygen-containing gas, which may be air or air diluted with inert fluids, is displaced from the borehole of a well outwardly through the unconsolidated pay zone containing oil. If the pay zone surrounding the borehole of a well has been depleted of oil for any reason, or if the formation contains a very high gravity oil or condensate, a readily cokable oil such as a crude oil or a residual oil can be placed in the borehole and displaced from the borehole into the unconsolidated formation before injection of the oxygen-containing gas. The oxygen-containing gas is initially displaced into the formation at a temperature below about 225° F. It is the usual practice to begin the operation by the displacement of the oxygen-containing gas at substantially the temperature of the unconsolidated formation and raise the oxygen-containing gas temperature rather quickly to 225° F. Further increases in temperature are made more slowly. A period of at least four hours should be used to raise the temperature of the oxygen-containing gas to 250° F. The period for increasing the temperature from the initial temperature to the final temperature at which the oxygen-containing gas is displaced into the formation is preferably at least about 48 hours. The particular time-temperature schedule of the injected gas below 250° F. is not highly critical, but it is preferred that the rate of temperature increase be substantially uniform. For example, if the temperature increase is stepwise, three or more substantially equal steps should be used. It will be desirable to run preliminary tests on oil from the unconsolidated sands whenever a coking operation is to be performed to aid in selection of the desired time-temperature schedule, but the schedule of four hours to 250° F. and 48 hours to the final temperature has an adequate margin of safety to permit its use on virtually all crude oils without danger of initiating combustion, either too close to, or which would move too close to, the borehole wall, which would destroy coke formed adjacent the borehole wall.

The temperature and pressure of the unconsolidated formation will also influence the rate at which the temperature of the injected gas can be raised. Increases in temperature or increases in pressure of the unconsolidated formation increase the reaction rate and make necessary slower initial raising of the temperature of the injected oxygen-containing gas, however, the effect of pressure is relatively minor compared to the effect of temperature on the rate of reaction between the oil and the oxygen-containing gas. If the process is used in a deep formation initially at a high temperature, the formation can be cooled, for example, by injection of a cool inert gas or liquid, such as water, before displacing an oxygen-containing gas into the formation.

The temperature of the oxygen-containing gas displaced into the formation is gradually increased at a substantially uniform rate in either a continuous or stepwise manner to a final temperature in the range of 350° to 500° F. adapted to produce a coke having adequate strength and a low solubility in oil. Suitable means for obtaining the desired temperature of the injected gas are, for example, downhole burners and electric heaters. Tests on cores of unconsolidated sands saturated with a readily cokable oil in which air is displaced through the unconsolidated sand at a temperature of approximately 300° F. have resulted in the formation of little, if any, coke, and have not produced the desired consolidation of the sand. In those experimental runs at air injection temperatures less than 350° F. in which coke was formed, the coke was soluble in hydrocarbon solvents. The temperature of the air displaced from the borehole into the formation should not exceed 500° to 600° F. It has been found that oxygen-containing gas temperatures in excess of 600° F. cause a marked decrease in the strength of the coked mass

adjacent the borehole. The following examples illustrate the process of this invention.

EXAMPLE 1

A thin-walled stainless steel tube, 5 inches in diameter and 5 feet long, was packed with sand and saturated with a crude oil having a gravity of 15.8° API from the Fruitvale field in California. A jacket around the tube provided an annular space surrounding the tube into which nitrogen was introduced to permit maintenance of the desired pressure within the tube without exposing the thin-walled tube to high pressure differences. Thermocouples were located at regular intervals through the packed sand. After air flow through the tube was established, the air was heated prior to displacement into the sand in accordance with the schedule set forth in Table I. The run was ended when temperatures within the 5-inch tube indicated that combustion was occurring. The air flux through the tubing was maintained at approximately 29,000 std. cu. ft./sq. ft./hr. and the outlet pressure of the tubing was maintained at approximately 750 lbs./sq. in.

EXAMPLE 2

A 5-inch tube, 5 feet long, was packed with sand which was then saturated with a Fruitvale crude oil having a gravity of 15.8° API. Thermocouples were positioned at regular intervals along the length of the tubing and the tubing provided with a jacket suitably connected with a source of nitrogen for maintaining the desired pressure on the outer surface of the tube. Air was passed through the tube to establish premeability and thereafter adjusted to maintain an air flux of approximately 30,000 std. cu. ft./sq. ft./hr. The pressure at the outlet of the tube was maintained at approximately 400 lbs./sq. in. gauge. The temperature of the air introduced into the tube was gradually increased in accordance with the schedule set forth in Table I and the temperatures indicated by the thermocouples recorded. The results of the tests of Examples 1 and 2 are presented in Table I.

Table I

Example 1			Example 2		
Time, min.	T, ° F., Injected Air	T, ° max., F.	Time, min.	T, ° F., Injected Air	T, ° max., F.
45	<65	<65	0	180	180
75	165	170	55	210	210
105	165	165	115	230	230
135	300	295	175	250	240
162	385	395	235	280	280
190	395	1,440	295	310	310
161	400	1,700	355	320	335
			475	390	420
			535	395	410
			595	390	400
			655	380	390

It will be noted from Table I that the rapid increase to an air inlet temperature of 395° F. in 2 hours and 40 minutes resulted in the initiation of combustion within the tubing, as indicated by a maximum temperature of 1700° F. The maximum temperature was indicated at a thermocouple located at a point about two-thirds of the distance to the outlet end of the tube. Similar tests have shown that if the injection of oxygen-containing gases is continued, reverse combustion occurs and the peak temperature moves toward the inlet end of the tube. When the temperature of the inlet air was increased more slowly, as in Example 2, in which approximately 8 hours were required to reach a temperature of 390° F., combustion was not initiated in the tube and a strong unitary mass of sand particles bonded with coke was produced.

The rates of raising the temperature of the injected air set forth in Table I are somewhat higher than are possible in subsurface formations. The radial flow pattern of

gases displaced from a well into a formation causes a rapid reduction in the flux as the distance into the formation increases and prevents maintenance of the high air flux used in the experimental tubes. Field tests have indicated that slower rates of increasing the temperature of the injected oxygen-containing gas are required in the field than in the experimental cores. For example, in a test in the Fruitvale field, air injection was commenced at the bottom hole temperature of 120° F. Four days later, propane was displaced down the well and burned in a borehole burner at a rate which gave a calculated temperature of the mixture of combustion products and air of approximately 330° F. Four hours later, the rate of fuel supplied to the burner was reduced to give a calculated temperature of 234° F. Analysis of gas produced the same day at an offset well 500 feet away indicated, by an increase in CO₂ and the appearance of nitrogen, that combustion had occurred. Effective consolidation of the sand was not obtained.

In the Santiago field in California, air was injected into the underground oil-bearing formation for 24 hours at the reservoir temperature. The temperature of the air was then increased to 150° F. by control of the rate of supplying propane gas to a burner in the borehole. The temperature of the injected gas was increased to 200° F. over an 8-hour period by increasing the rate of fuel supply to the burner and then held for 16 hours at 200° F. The temperature of the injected gas was then increased to 250° F. over an 8-hour period and held for 16 hours at 250° F. The sequence of raising the temperature and then holding the temperature was continued until the temperature of the gases displaced into the formation reached 400° F. No detrimental combustion of the oil in the formation surrounding the borehole was experienced, and subsequent production of oil from the well indicated that the sands were consolidated adequately to prevent flow of sand into the well. The procedure in the Santiago field was conservatively designed to prevent detrimental combustion. Subsequent laboratory tests show that more rapid increases in the temperature of the air displaced into the formation can be used without causing destructive combustion of coke formed adjacent the borehole wall.

Suitable consolidation of the formation and prevention of forward burning which destroys coke formed adjacent to the borehole of the well cannot be obtained merely by maintaining a low temperature of oxygen-containing gas displaced into the formation. A number of field tests of in-situ combustion processes have shown that continued injection of oxygen-containing gases at the formation temperature into the formation will eventually cause combustion to be initiated at some distance from the injection well. Once the combustion is initiated, the temperature will build up to excessive levels and eventually reverse combustion occurs causing the combustion front to move to the injection well. Continued displacement of oxygen-containing gas after the combustion front reaches or approaches the injection well causes a second reversal in the direction of movement of the combustion front to forward combustion which completely consumes any coke deposited adjacent the injection well. It is necessary to raise the temperature of the injected gas to condition the oil in the formation adjacent the injection borehole, whereby the subsequent combustion will not travel by reverse combustion to destroy coke reaching the desired thickness of the sleeve of coke bonded particles surrounding the borehole.

The permissible rate of raising the temperature of the oxygen-containing gases displaced into the formation is dependent upon the rate of injection of the oxygen-containing gases. Higher rates of injection of the oxygen-containing gas result in more rapid removal of the heat of reaction of the oil with the oxygen-containing gas, and thereby reduce the maximum temperature in the oil-bearing formation. Experimental runs similar to those

described in Examples 1 and 2 were conducted with different rates of air flow through sample tubes one inch in diameter. The results are shown in Table II.

Table II

Example	Air Flux, std. cu. ft./ sq. ft./hr.	T., ° F., Injected Air	T., max., ° F.	Outlet Pressure, p.s.i.	Coke
3-----	3, 180	300-360	1, 020	260-300	Sand Burned Clean.
4-----	8, 750	320-370	460	225-270	Firm.
5-----	27, 000	390-410	730	440-545	Firm.
6-----	4, 350	290-305	310	590-600	None.
7-----	4, 600	280-315	320	760	None.

It will be noted from Example 3 in Table II that a maximum temperature of 1020° F. was reached and the sand was burned clean when the air flux was 3180 std. cu. ft./sq. ft./hr. An increase in the air flux to 8750 std. cu. ft./sq. ft./hr. resulted in a maximum temperature of 460° F. and the formation of firm coke as shown in Example 4. Example 5 presents results of a run in which the temperature of the injected air was increased more rapidly to a higher temperature. By increasing the air flux to 27,000 std. cu. ft./sq. ft./hr., it was possible to produce a core that was firmly bonded by coke. It has been found that an air flux of 500 cu. ft./sq. ft./hr. is not high enough to prevent destructive combustion even where the temperature of the injected air is as low as 200° F. A flux in excess of 1000 std. cu. ft./sq. ft./hr. should be used. The minimum flux of the oxygen-containing gas is the minimum flux at the outer boundary of the coked zone. Suitable regulation of the flux at the borehole wall will be required to insure at least the minimum flux at the outer boundary of a coked zone of the desired thickness.

Although control of the rate of injection of the oxygen-containing gas allows some modification of the rate of increasing the temperature of the injected air, control of the temperature is the most effective way to prevent destructive combustion of the coke. Extremely large compressor capacity would be required to maintain the very high air flux of Example 5 along the borehole wall of the entire thickness of an oil-bearing formation. Moreover, the radial flow pattern of the injected gases results in low air fluxes a short distance from the borehole wall. The radial flow pattern has the advantage, however, of higher fluxes near the borehole wall which cause increasing opposition near the borehole to movement of the combustion front toward the borehole. The use of very high flow rates to prevent ignition is effective when production is through a window or perforations in casing and it is only necessary to consolidate with coke around such openings in the casing.

Dilution of the oxygen-containing gas with inert gases such as flue gases or with water is effective in delaying ignition, compared with injection of air alone, primarily in providing a larger amount of fluid to carry heat of reaction from the formation immediately adjacent the borehole of the injection well. Apparently an excess of oxygen is usually present and the rate of reaction of the oil with the oxygen is substantially independent of the concentration of oxygen in the injected gases except at very high dilution rates. Dilution of the oxygen-containing gas with an inert gas and increasing the rate of injection of the oxygen-containing gas are possible techniques allowing a more rapid increase in the temperature of the injected oxygen-containing gas, but are inferior to temperature control of the injected oxygen-containing gas as a means of insuring the creation of a strong coke bonding the sand particles together.

The injection into the formation of oxygen-containing gases at a temperature in excess of about 500° F., and particularly at a temperature in excess of about 600° F., impairs the strength of the coke bonding the particles

together. Although temperatures higher than 500° F. are reached at some distance from the borehole wall when the temperature of the injected gas is below 500° F., those higher temperatures do not occur adjacent the borehole wall in the process of this invention. As a result, ignition and forward burning in the formation at some distance in the formation do not destroy the bonding of the sand particles near the borehole.

The impairment of the strength of masses of sand bonded with coke in accordance with the process of this invention is illustrated by the effect of heating cores of sand, in which oil present therein had been coked by air at a maximum injection temperature of 400° F., in a muffle furnace. Heating the cores to a temperature of 500° F. for a period of four hours resulted in a marked increase in the compressive strength of the cores. However, heating the cores in a muffle furnace at a temperature of 700° F. for a period of four hours caused a reduction of the compressive strength of the cores to about 30 percent of the strength of the cores heated to 500° F. Heating to a temperature of 800° F. resulted in substantially complete destruction of the strength of the core. The results of the several tests indicated that heating in a muffle furnace to a temperature of 600° F. would reduce the strength of the cores to approximately 50-60 percent of the strength they possessed after heating to 500° F. Only natural convection of air occurred in the muffle furnace; hence, it could be expected that passing air at temperatures of 600° F. or more through the cores would cause an even more drastic reduction of the strength of cores than the treatment in the muffle furnace.

It is a unique characteristic of this invention that the gases displaced through the oil-bearing formation to form the strong coke bond contain oxygen. The difficulties with initiation of combustion, and consequently destruction of the coke bond, can readily be prevented by passing a completely inert gas at a high temperature through the oil-bearing formation. The inert gas will heat the formation, by giving up some of its sensible heat, to a temperature at which coking occurs. However, inert gases are not ordinarily available at the well site and can be provided only at substantial expense. Downhole burners must be operated with excess air to operate efficiently; hence, usually are not satisfactory sources of an inert gas.

We claim:

1. A method of consolidating an unconsolidated formation containing a cokable oil, comprising displacing an oxygen-containing gas at a temperature less than about 225° F. into the formation, continuing to displace the oxygen-containing gas into the formation while raising the temperature of the gas to about 250° F. over a period of at least about four hours, and continuing to displace an oxygen-containing gas into the formation while raising the temperature of the gas from 250° F. to a maximum temperature of 350° F. to 600° F. over a period of at least about 48 hours whereby oil in the formation is coked to bond particles thereof into a strong mass, the flux of the oxygen-containing gas being in excess of 1,000 std. cu. ft./sq. ft./hr. as said gas enters the formation and the rate of raising the temperature being adapted to avoid combustion of oil adjacent the borehole.

2. A method as set forth in claim 1 in which the oxygen-containing gas is air.

3. A method as set forth in claim 1 in which the oxygen-containing gas is a mixture of combustion products and air.

4. A method of consolidating an unconsolidated formation penetrated by the borehole of a well, said unconsolidated formation containing a cokable oil, comprising displacing an oxygen-containing gas down the borehole of the well and into the formation at a temperature below 225° F. and flux adapted to avoid combustion of oil in the formation immediately adjacent the borehole, and continuing to displace the oxygen-containing gas down the borehole of the well and into the formation

while raising the temperature of the gas to 350° to 600° F., the rate of raising the temperature of the oxygen-containing gas displaced into the formation being adjusted to avoid combustion of oil in the formation adjacent the borehole wall whereby oil in the formation is coked to bond particles thereof into a strong mass.

5. A method as set forth in claim 4 in which casing is set through the unconsolidated formation, a notch is cut in the casing, and the oxygen-containing gas is displaced into the unconsolidated formation through the notch in the casing.

6. A method of consolidating an unconsolidated formation penetrated by the borehole of a well, comprising displacing a cokable oil down the borehole of the well and into said unconsolidated formation, displacing an oxygen-containing gas down the borehole of the well and into the formation at a temperature and flux adapted to avoid combustion of oil in the formation immediately adjacent the borehole, continuing to displace the oxygen-containing gas down the borehole of the well and into the formation while raising the temperature of the gas to 350° to 600° F., the rate of raising the temperature of the oxygen-containing gas displaced into the formation being adjusted to avoid combustion of oil in the formation adjacent the borehole wall whereby oil in the formation is coked to bond particles thereof into a strong mass, the flux of the oxygen-containing gas being in excess of 1,000 std. cu. ft./sq. ft./hr. at the borehole wall and the rate of raising the temperature being adapted to avoid combustion of oil adjacent the borehole.

7. A method of consolidating an unconsolidated formation containing cokable oil, comprising displacing an oxygen-containing gas mixed with a diluent down the borehole of a well and into the unconsolidated formation at a temperature less than 225° F., continuing to displace the mixture of oxygen-containing gas and diluent into the unconsolidated formation at a temperature and flux adapted to avoid combustion of oil adjacent the borehole wall while raising the temperature of the oxygen-containing gas and diluent injected into the formation to a temperature in the range of 350° to 600° F., whereby oil in the formation is coked to bond particles thereof into a strong mass.

8. A method of consolidating an unconsolidated formation for a desired distance from the borehole of a well penetrating the unconsolidated formation, said unconsolidated formation containing a cokable oil, comprising displacing an oxygen-containing gas down the borehole of the well and into the unconsolidated formation at a temperature less than 225° F., continuing to displace the oxygen-containing gas into the unconsolidated formation while raising the temperature of the oxygen-containing gas at a substantially uniform rate adapted to avoid combustion of oil adjacent the borehole of the well to a temperature in the range of 350° to 600° F., the flux of the oxygen-containing gas at said desired distance from the borehole being in excess of 1000 std. cu. ft./sq. ft./hr.

9. A method as set forth in claim 8 in which the desired distance from the borehole is at least one foot.

10. A method of consolidating an unconsolidated formation penetrated by the borehole of a well, said unconsolidated formation containing cokable oil, comprising displacing a hydrocarbon fuel and air down the well and burning said fuel in the well, the rate of injection of the air being such as to maintain the temperature of the combustion products below 225° F., increasing the ratio of fuel to air to raise the temperature of the combustion products to 350° to 600° F. whereby oil in the formation is coked to bond particles thereof into a strong permeable mass, the rate of increasing the fuel to air ratio being substantially uniform and adapted to avoid combustion of oil adjacent the borehole wall.

11. A method of consolidating an unconsolidated formation penetrated by the borehole of a well, said unconsolidated formation containing a cokable oil, compris-

ing displacing air down the well and into the formation at a temperature below 225° F., continuing to displace air down the well and into the formation while heating the air to raise the temperature of the air displaced into the formation to the range of 350° to 600° F., the rate of increasing the temperature of the air being substantially uniform and adapted to avoid combustion of oil in the formation adjacent the well, whereby oil in the forma- 5

tion is coked to bond particles thereof into a strong permeable mass.

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