MECHANISM of WATER FLOODING in the PRESENCE of FREE GAS

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ABSTRACT

Experimental studies covering a wide range of core materials and fluid properties have been conducted to determine the mechanism of oil displacement by water in a partially gas-saturated porous medium. In all instances, the presence of a gas phase was found to have a beneficial effect in reducing residual oil saturations. The practical significance of this benefit is discussed, and a simplified procedure is outlined for evaluating the effects of free gas on water flooding by means of short core tests.

INTRODUCTION

In addition to oil and water, reservoirs subjected to water flooding frequently contain, also, a gas phase. Common engineering procedures account for the presence of this "free gas" only from the viewpoint of volumetric balance, implying that the only role of the gas consists of providing "fill up" space. It is usually visualized that during the initial stages of the water invasion, the oil, moving ahead of the water, displaces part of the gas and that subsequently the remaining portion of the gas phase is totally compressed and dissolved in the advancing oil bank. Thus, consideration of a two-phase, water-oil flooding mechanism supplies an adequate basis for predictions of oil recovery if the pressure build-up caused by the flood is sufficiently great, so as to reduce the free gas saturation to a negligible value in any portion of the reservoir by the time that portion is reached by the advancing flood water. In many instances, however, waterflooding operations are carried out when the reservoir pressure is still relatively high so that the pressure build-up associated with the water flood may not result in complete dissipation of the gas phase. Under such circumstances it is necessary to ascertain whether or not the presence of free gas has an effect on waterflood behavior and, if so, to account for any such effect in the evaluation of field operations.

The difficulties encountered in attempting to arrive at a comprehensive picture of the displacement mechanism of oil by water in the presence of free gas stem from the fact that most of the published data on this subject were obtained under conditions that were either not clearly representative of those existing in a reservoir or not sufficiently controlled to permit evaluation of the effects specifically caused by the gas phase. Some of the most precise data found in the literature were obtained in tests using a "static" gas phase created prior to each water flood by circulating oil through partly gas-saturated cores until a "trapped," residual gas saturation was established throughout the system.[1] Other investigations were conducted under more representative conditions where the gas phase was free to move during the water flood; but in most cases the results of these tests were obscured by auxiliary phenomena which arise from the compressibility and solubility of the gas and preclude quantitative conclusions.[2,3,4]

Prior to water flooding, a reservoir usually contains oil and gas, distributed in a manner in which both are free to move. Thus, the principal objective of the present studies was to determine the type of displacement mechanism occurring when water invades a porous medium containing oil and a "mobile" gas phase. Further-

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[1]References given at end of paper.

more, it was desired to investigate the effect of free gas on waterflood oil recovery for a wide range of core materials and fluid properties.

EXPERIMENTAL PROCEDURE

Seven cores representing five different types of water-wet and oil-wet porous media were used in the present studies. The characteristics of these cores, ranging from 2 to 18 in. in length, are summarized in Table 1. The samples were mounted in steel core holders, designed for operating pressures up to 1,800 psi and provided with "O" ring-sealed, steel end-plates. The sealing of the core material in the holder was accomplished by means of a low melting point bismuth alloy which has the property of expanding upon solidifying.

In order to study the effects caused specifically by the presence of a third phase, the free gas, on the displacement mechanism of oil by water, it was desirable to minimize any gas compressibility and solubility phenomena. To achieve this purpose, the flooded systems were maintained at a relatively high pressure level (about 1,100 psi) as compared to the flowing pressure differentials (about 50 psi) imposed across the systems during the floods, and all liquids used in the flooding tests were pre-saturated with gas at 1,100 psi. Helium, which is only very slightly soluble in oil and water, was used as the gas phase. The oils employed in the experiments were Soltrol "C" (Phillips Petroleum Co.), Marcol "JX" (Esso), and Primol "D" (Esso), having viscosities of about 1.4, 22.0, and 116 cp, respectively at 76°F.

A constant rate precision pump was used to deliver mercury to a battery of transfer vessels to displace the helium-saturated liquids (brine or oil) through their respective filters into the core. The pressure level of the flow system was controlled by means of a back pressure regulator at the exit of the core. Produced fluids passed through this regulator and were then measured volumetrically at atmospheric pressure. The absolute inlet and outlet pressures of the flow system were measured using two (Bourdon type) Heise precision pressure gauges and the pressure drop across the test sample was determined by means of a Statham differential pressure gauge.

In all of the tests, except those performed on the dri-filmed Alundum cores, connate water was established prior to water flooding. To avoid changes in flooding behavior that could be brought about by rock compaction or variations in fluid properties, all flooding tests, including the reference floods, were performed with helium-saturated liquids and at the same pressure level, 1,100 psi. After a test sample had been saturated with the appropriate oil, one of the three following types of operations was carried out:

1. *Reference water floods,* performed without any free gas in the core, to provide a standard of comparison for evaluating the water floods in the presence of free gas.

2. *Water floods in presence of a mobile gas phase.* A mobile gas phase was established prior to water flooding by driving the core with helium until the amount of oil displaced indicated that the desired value of gas saturation was attained.

3. *Water floods in presence of a trapped gas phase.* In preparation for this type of test a mobile gas phase was first established in the manner described under Item 2. Subsequently, the core was "oil-flooded" with helium-saturated oil which displaced part of the mobile gas phase, resulting in the establishment of a certain residual gas saturation at which the gas became discontinuous and unable to move. The value of this residual, "trapped" gas saturation was determined by volumetric balance, and the water flood was then initiated.

At the termination of each flooding test the cores were depressured and cleaned by flushing with about 10 pore volumes of acetone, driving with dry nitrogen and finally evacuating for a period of about 24 hours to remove all traces of volatile material.

Each waterflood test was performed at a constant rate of water injection. This rate was chosen sufficiently high so as to eliminate capillary end effects and to insure stabilized flooding behavior representative of field performance.[5]

TABLE 1—CORE PROPERTIES

Core No.	Core Material	Wettability	Length Inches	Diam. Inches	Porosity Per Cent	Air Permeability Millidarcys
T375	Torpedo Sandstone	Water-Wet	10.0	1.95	22.8	375
T640	Torpedo Sandstone	Water-Wet	8.5	1.95	24.9	640
A414	Untreated Alundum	Water-Wet	12.0	1.46	26.6	414
R146	Redwater Limestone	Water-Wet	13.2	3.41	19.7	146
B279	Berea Sandstone	Water-Wet	18.0	1.92	19.3	279
DFA87	Dri-Filmed Alundum	Oil-Wet	12.0	1.49	25.8	87
DFA88	Dri-Filmed Alundum	Oil-Wet	2.0	1.49	26.2	88

RESULTS AND DISCUSSION

The results of this investigation are based on a total of 44 flooding tests of which 14 were conducted in the presence of an initially mobile gas phase, 16 were conducted in the presence of a trapped gas phase, and 14 were reference floods performed in the absence of gas. A summary of the pertinent data is presented in Table 2.

GENERAL ANALYSIS OF FLUID DISPLACEMENTS

The flooding behavior observed in all tests conducted in the presence of an initially trapped gas phase is illustrated by the data shown in Fig. 1. As may be seen, the gas saturation of the core remains constant, and only oil, then subsequently both oil and water are produced during the flood. Thus a water flood conducted in the presence of a trapped gas phase corresponds

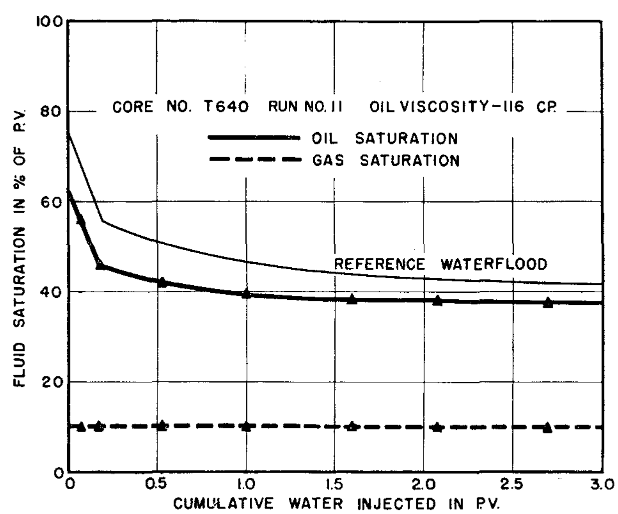

FIG. 1—WATER FLOOD IN THE PRESENCE OF TRAPPED GAS.

in reality to a two-phase, water-oil displacement evolving in that portion of the pore space which is not occupied by the gas phase.

In all of the flooding tests conducted in the presence of an initially mobile gas phase the production history was found to follow the same pattern which is illustrated by the curves of Fig. 2. At the beginning of the flood only free gas was produced. Subsequently, all gas production ceased (cf. line 00′, Fig. 2) and only oil appeared in the effluent. After water breakthrough, indicated by the line WW′, oil and increasing amounts of water were produced simultaneously until the flood was terminated.

The above described type of production history indicates that the displacement of oil by water from a porous medium containing a continuous mobile gas phase results in the formation of two distinct fluid saturation profiles, namely an oil bank followed by a water bank, moving in sequence throughout the flow system, as schematically illustrated in Fig. 3. The oil bank, formed upon the injection of water, displaces part of the initial mobile gas phase, leaving behind a certain amount of residual gas. This residual gas is no longer

TABLE 2—SUMMARY OF FLOODING DATA

Run No.	Core No.	μ_o/μ_w	Type of Flood	C.W. % of P.V.	S_g Initial % of P.V.	S_o, % of P.V. Initial	At WBT	At 1 P.V.	At 3 P.V.	S_g Final % of P.V.	ΔS_o, % of P.V. At WBT	At 1 P.V.	At 3 P.V.	S_w Final % of P.V.
1	T640	1.3	Ref.	22.7	0	77.3	29.6	29.6	29.6	0	0	0	0	70.4
2	T640	1.3	Ref.	26.0	0	74.0	28.7	28.7	28.7	0	0	0	0	71.3
3	T640	1.3	MG	24.5	10.0	65.5	24.8	24.8	24.8	9.7	4.4	4.4	4.4	65.5
4	T640	1.3	TG	24.2	11.6	64.2	21.4	21.4	21.4	11.6	7.8	7.8	7.8	67.0
5	T640	1.3	TG	26.0	19.0	55.0	19.4	19.4	19.4	19.0	9.8	9.8	9.8	61.6
6	T640	1.3	MG	25.7	21.4	52.9	21.1	21.1	21.1	19.5	8.1	8.1	8.1	59.4
7	T640	1.3	MG	25.9	44.8	29.3	13.6	13.6	13.6	24.9	15.6	15.6	15.6	61.5
8	T640	1.3	TG	25.1	27.1	47.8	16.7	16.7	16.7	27.1	12.5	12.5	12.5	56.2
9	T640	107	Ref.	25.0	0	75.0	55.6	46.5	41.6	0	0	0	0	58.4
10	T640	107	TG	26.0	10.2	63.8	45.8	39.6	37.7	10.2	9.8	6.9	3.9	52.1
11	T640	107	TG	25.9	10.8	63.3	45.1	40.3	37.4	10.8	10.5	6.2	4.2	51.8
12	T640	107	MG	25.6	29.5	44.9	40.8	37.1	35.6	14.0	14.8	9.4	5.0	50.4
13	T375	1.3	Ref.	21.9	0	78.1	28.8	28.8	28.8	0	0	0	0	71.2
14	T375	1.3	Ref.	22.6	0	77.4	29.1	29.1	29.1	0	0	0	0	70.9
15	T375	1.3	TG	22.6	11.8	65.6	22.3	22.3	22.3	11.8	6.7	6.7	6.7	65.9
16	T375	1.3	MG	22.7	18.2	59.1	24.1	24.1	24.1	13.9	4.9	4.9	4.9	62.0
17	T375	1.3	TG	22.6	20.5	56.9	19.0	19.0	19.0	20.5	10.0	10.0	10.0	60.5
18	T375	107	Ref.	24.4	0	75.6	54.0	45.7	40.2	0	0	0	0	59.8
19	T375	107	MG	24.4	26.6	49.0	40.5	37.4	35.7	14.5	13.5	8.3	4.5	49.8
20	T375	107	TG	25.7	15.4	58.9	40.7	37.1	35.4	15.4	13.3	8.6	4.8	49.2
21	A414	1.55	Ref.	15.4	0	84.6	25.3	25.3	25.3	0	0	0	0	74.7
22	A414	1.55	MG	14.6	43.8	41.6	17.0	17.0	17.0	19.2	8.3	8.3	8.3	63.8
23	A414	1.55	MG	14.6	22.8	62.6	19.5	19.5	19.5	12.2	5.8	5.8	5.8	68.3
24	R146	1.3	Ref.	21.0	0	79.0	42.4	36.5	32.4	0	0	0	0	67.6
25	R146	1.3	MG	19.9	15.7	64.4	37.5	32.3	27.6	10.0	4.9	4.2	4.8	62.4
26	R146	1.3	MG	20.0	24.2	55.8	35.3	27.9	24.2	15.9	7.1	8.6	8.2	59.9
27	B279	1.3	Ref.	26.0	0	74.0	36.7	36.7	36.7	0	0	0	0	63.3
28	B279	1.3	MG	25.4	29.2	45.4	28.4	28.4	28.4	18.0	8.3	8.3	8.3	53.6
29	DFA87	1.55	Ref.	0	0	100	44.6	39.0	31.8	0	0	0	0	68.2
30	DFA87	1.55	Ref.	0	0	100	44.7	39.0	32.0	0	0	0	0	68.0
31	DFA87	1.55	MG	0	19.7	80.3	39.8	35.6	32.0	14.9	4.9	3.4	-0.1	53.1
32	DFA87	1.55	TG	0	15.0	85.0	38.1	35.5	32.2	15.0	6.6	3.5	-0.3	52.8
33	DFA87	1.55	MG	0	32.8	67.2	37.6	34.5	31.5	18.4	7.1	4.5	0.4	50.1
34	DFA87	1.55	TG	0	19.6	80.4	36.4	33.6	31.9	19.6	8.3	5.4	0	48.5
35	DFA87	1.55	MG	0	46.7	53.3	36.6	33.4	32.1	21.5	8.1	5.6	-0.2	46.5
36	DFA87	24.4	Ref.	0	0	100	82.5	65.0	55.5	0	0	0	0	44.5
37	DFA87	24.4	TG	0	8.2	91.8	74.5	57.7	49.0	8.2	8.0	7.3	6.5	42.8
38	DFA87	24.4	TG	0	10.9	89.1	73.0	56.2	48.0	10.9	9.5	8.8	7.5	41.1
39	DFA87	24.4	TG	0	11.9	88.1	70.9	53.5	46.2	11.9	11.6	11.5	9.3	41.9
40	DFA87	24.4	TG	0	13.0	87.0	68.8	52.9	43.1	13.0	13.7	12.1	12.4	43.9
41	DFA88	1.55	Ref.	0	0	100	44.9	40.9	32.4	0	0	0	0	67.6
42	DFA88	1.55	TG	0	16.0	84.0	39.0	36.8	32.1	16.0	5.9	4.1	0.3	51.9
43	DFA88	24.4	Ref.	0	0	100	85.4	69.8	58.5	0	0	0	0	41.5
44	DFA88	24.4	TG	0	11.3	88.7	75.0	59.5	50.2	11.3	10.4	10.3	8.3	38.5

μ_o/μ_w - Oil-Water Viscosity Ratio
Ref. - Reference Flood
TG - Flood in Presence of Trapped Gas
MG - Flood in Presence of Initially Mobile Gas

C.W. - Connate Water
S_g - Gas Saturation
S_o - Oil Saturation

WBT - Water Breakthrough
ΔS_o - Reduction in Oil Saturation Caused by Presence of Gas
S_w - Water or Brine Saturation

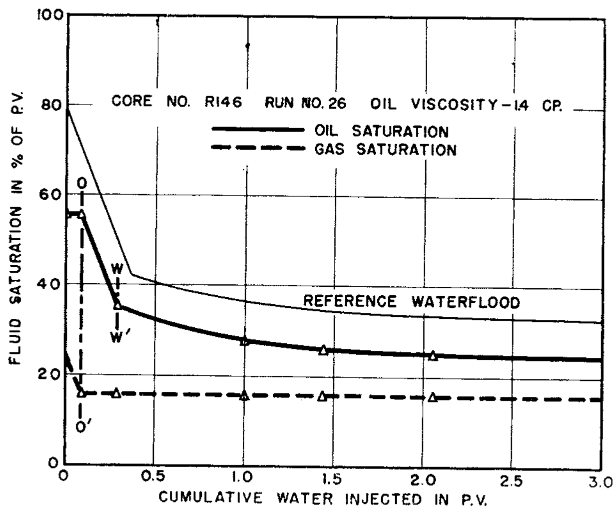

FIG. 2—WATER FLOOD IN THE PRESENCE OF INITIAL MOBILE GAS.

free to move and should be considered "trapped", i.e., distributed in the form of discontinuous bubbles or filaments throughout the pore space. The oil filling up the pore space around the trapped gas is then displaced in turn by the advancing water bank.

As gas production ceased in all tests when oil first appeared in the effluent, the obvious conclusion is that a sharp saturation front exists between the oil bank and the mobile gas. The existence of this "piston-like" front can be expected under all circumstances because of the low viscosity ratio of displaced to displacing fluid, and also because the displaced gas will always assume the role of the non-wetting fluid.

It will be noted that the sharpness of the water bank is likely to be much less pronounced than that of the oil bank, and that the water-oil saturation profile can assume different shapes according to the core material and the oil to water viscosity ratio. However, the build-up of two successive saturation banks (cf. Fig. 3) can be anticipated under all circumstances and is considered to be a basic feature of the mechanism of water flooding in presence of a mobile gas phase.

Relationship Between Mobile and Trapped Gas Saturations

Additional information concerning the nature of the waterflood mechanism in the presence of a mobile gas phase may be obtained from analysis of the data pertaining to the displacement of the free gas. Correlations between initial mobile gas saturations and the corresponding residual trapped gas saturations are shown in Fig. 4 for Torpedo sandstone and dri-filmed Alundum. Soltrol "C" was the oil phase used in both cases. The dark symbols correspond to the runs in which gas was displaced by oil flooding and the light symbols denote runs in which the gas displacement resulted from water flooding in the presence of an initially mobile gas phase. It is seen that the data points for each core material yield a single correlation, regardless as to whether the porous medium containing originally mobile gas and oil is subjected to water or to oil injection. This finding confirms that water flooding in the presence of a mobile gas phase results in the establishment of an oil bank ahead of the injected water, and that it is this oil bank which displaces a portion of the gas phase and traps the remainder.

In general the relationship between trapped and mobile gas was found to depend upon the core material and the type of oil used. For a given core material and initial mobile gas saturation, the amount of gas trapped by the light oil was always greater than that trapped by the more viscous oils.

Relationship Between Residual Oil and Trapped Gas Saturations

In all the water floods conducted in the presence of a gas phase, the oil saturations attained at successive flooding stages were found to be lower than those observed for the reference floods performed in the absence of gas. Correlations of the data obtained with water-wet (Torpedo sandstone) and oil-wet (dri-filmed Alundum) cores are shown in Figs. 5 and 6, respectively. In these figures the oil saturations obtained at three flooding stages, namely at water breakthrough, after injection of one pore volume of water and after injection of three pore volumes, are plotted as functions of the trapped gas saturations present in the cores during the flooding tests. The dark symbols are representative of the floods performed in the presence of an initially trapped gas phase while the light symbols correspond to tests in which the gas was initially mobile and became trapped during the progress of the flood.

A single line is presented in Fig. 5 for correlation of the results pertaining to the flooding of the light oil (Soltrol C) from Torpedo sandstone, because in this strongly water-wet material the displacement of low viscosity oil is almost piston-like. Thus, in this case, consideration of a single stage, the amount of water breakthrough, is sufficient to define the flooding behavior. A similar piston-like displacement of low viscosity oil was also observed in the Berea and untreated Alundum cores. However, with increasing oil viscosities, and in the less water-wet or the preferentially oil-wet media, the sharpness of the water bank became less pronounced, resulting in increasing amounts of oil production after water breakthrough.

The results presented in Figs. 5 and 6 clearly indicate that there is a definite relationship between the trapped gas saturation and the oil saturation attainable at a given flooding stage. For each core material and oil viscosity, all the data points corresponding to a given flooding stage lie on the same correlating line whether the gas phase is trapped prior to or during the water flood. This finding corroborates the mechanism illustrated in Fig. 3, which indicates that any reduction in residual oil saturation below that observed in the absence of gas should be attributed to the amount of trapped gas which exists at the advancing water bank.

For purposes of discussion and evaluation it is con-

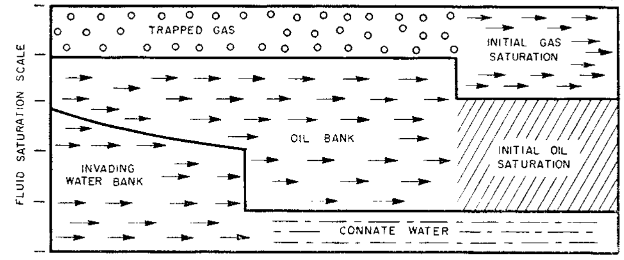

FIG. 3—SCHEMATIC SATURATION PROFILE ILLUSTRATING THE DISPLACEMENT OF OIL BY WATER IN THE PRESENCE OF AN INITIALLY MOBILE GAS PHASE.

venient to introduce the concept of gas "effectiveness". The "effectiveness" of the gas phase can be defined as the ratio of the reduction in oil saturation at a given flooding stage (below that obtained in the reference flood at the same stage) to the trapped gas saturation causing this reduction. For example, referring to Fig. 5, it is seen that for the case of a 116 cp oil in Torpedo sandstone material, the presence of 10 per cent of PV trapped gas yields an oil saturation of about 40 per cent of PV after injection of one pore volume of water, as compared to an oil saturation of 46 per cent of PV obtained in the absence of gas. Thus, the presence of 10 per cent of PV trapped gas has caused a decreased in oil saturation of 6 per cent of PV, and the "effectiveness" of the trapped gas at this particular flooding stage is 60 per cent. Similar evaluations for this system show the effectiveness of the gas to be about 100 per cent at water breakthrough and 35 per cent after injection of three pore volumes of water. A general summary of the values of gas effectiveness for the different core materials and fluids tested is presented in Table 3.

Examination of the values of gas effectiveness corresponding to the water flooding of light oil (cf. Table 3, also Figs. 5 and 6) suggests that the presence of a gas phase causes a decrease in the ultimate residual oil saturation in water-wet media, but that the gas has no effect on the ultimate residual oil in oil-wet media.* The reason for this dissimilar behavior may lie in the micro-configurations of the respective residual oil saturations. In water-wet materials it is believed that the ultimate residual oil is trapped by water and that the gas phase, which is in turn trapped within the oil, occupies a portion of the pore space which in the absence of gas would be occupied by oil. On the other hand, in the oil-wet material tested (in the absence of connate water) the ultimate residual oil is believed to be in the form of pendular rings around the contact points of the rock grains. This configuration should result whether the surrounding pore space is filled by gas or by water. Thus, in this oil-wet material, when the ultimate residual oil saturation is attained, the gas phase simply occupies space which in the absence of gas would be occupied by water.

*Experimental evidence is not available to indicate the effect of free gas on the ultimate residuals for floods in which a viscous oil was used. Because of the large volumes of water and length of time required, it was impractical to continue these floods until oil production ceased.

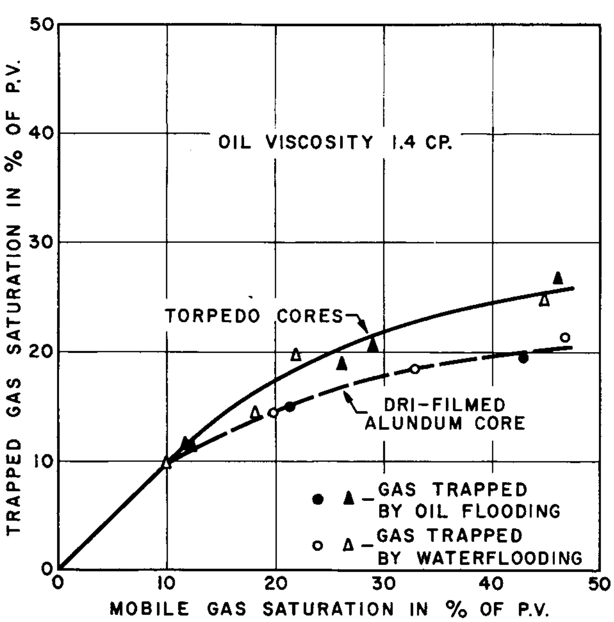

FIG. 4—DISPLACEMENT OF MOBILE GAS BY OIL AND WATER INJECTION.

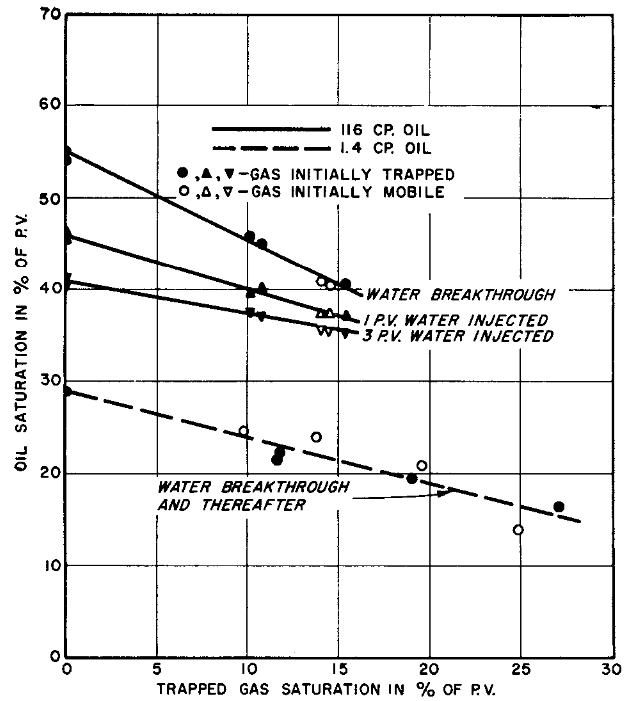

FIG. 5—RELATIONSHIPS BETWEEN TRAPPED GAS AND RESIDUAL OIL SATURATIONS, TORPEDO SANDSTONE CORES

RELATIONSHIP BETWEEN RESIDUAL OIL AND INITIAL MOBILE GAS SATURATIONS

For purposes of analysis the experimental results have been presented thus far in the form of correlations between residual oil and trapped gas saturations. Since in turn, for each core material and fluid system, the trapped gas was found to be a unique function of the initial mobile gas saturation, the residual oil saturations can also be directly correlated with—or determined as a function of—the mobile gas saturations existing at the initiation of the water flood. Such type of correlation which is of considerable practical interest is shown in Fig. 7. Presented in this figure are the relations between oil saturations attainable after injection of one

TABLE 3

SUMMARY OF GAS EFFECTIVENESS VALUES

CORE MATERIAL	CORE WETTABILITY	OIL VISCOSITY, cp.	TRAPPED GAS EFFECTIVENESS, % AT WBT	AT 1 P.V.	AT 3 P.V.
TORPEDO SANDSTONE	WATER-WET	116	100	60	35
DRI-FILMED ALUNDUM	OIL-WET	22	100	95	80
UNTREATED ALUNDUM	WATER-WET	1.4	45	45	45
REDWATER LIMESTONE	WATER-WET	1.4	48	48	48
BEREA SANDSTONE	WATER-WET	1.4	46	46	46
TORPEDO SANDSTONE	WATER-WET	1.4	50	50	50
DRI-FILMED ALUNDUM	OIL-WET	1.4	40	25	0

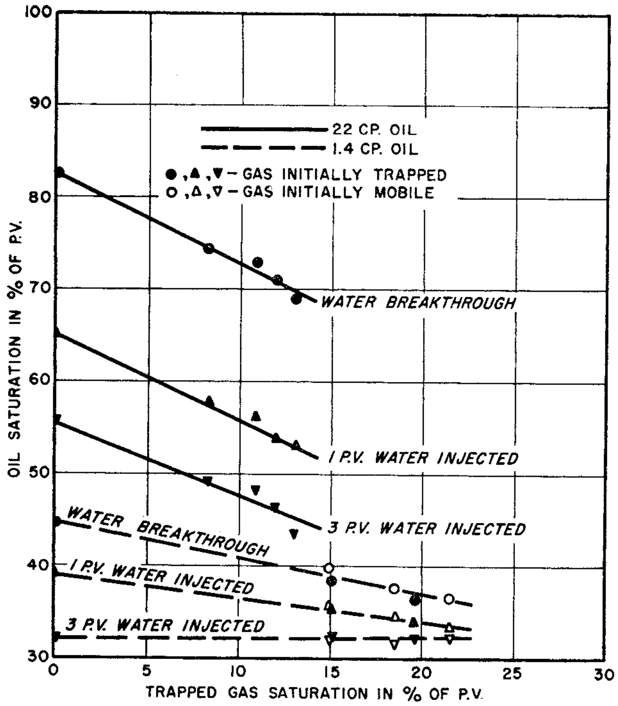

FIG. 6—RELATIONSHIPS BETWEEN TRAPPED GAS AND RESIDUAL OIL SATURATIONS, DRI-FILMED ALUNDUM CORE (DFA87).

pore volume of water and initial mobile gas saturations, for the Torpedo, Redwater and dri-filmed Alundum core materials.

In all cases the residual oil saturations attainable after one pore volume water injection are seen to decrease quite rapidly as the initial mobile gas saturation increases from 0 to 15 per cent of pore volume. With further increases in initial gas saturation the corresponding reductions in residual oil saturation become less pronounced. This is primarily due to the fact that the fraction of the mobile gas phase which is displaced during the water flood, and hence does not contribute to the lowering of the residual oil saturation, increases with increasing initial gas saturations (as may be seen from Fig. 4). A result of practical interest is that the presence of 15 per cent of pore volume free gas at the initiation of a water flood, a situation frequently encountered in fields to be waterflooded after primary production, can cause the residual oil saturation to be lowered by 3 to 7 per cent of pore volume in the case of a light oil, and by 8 to 10 per cent of pore volume in the case of viscous oils.

APPLICATIONS

EFFECTIVENESS OF THE GAS PHASE UNDER PRACTICAL CONDITIONS

In practice, waterflood operations are seldom carried beyond a total water injection of one to two pore volumes. Therefore, (while the observed effects of free gas on ultimate residual oil saturations may serve to round out the picture of the three-phase flooding mechanism) the results of practical interest are those pertaining to the effects of the gas phase during the early flooding stages. The values of gas effectiveness observed after injection of one pore volume of water are believed to provide a good illustration of the results attainable under field conditions. These values are listed in the shaded column of Table 3.

The practical significance of the effectiveness of the gas is that it represents a direct measure of the additional oil recovery over that which would be obtained in a flood where the gas phase is dissipated by compression and solution. The values of gas effectiveness then express this additional oil recovery as a fraction or per cent of the amount of gas that remains in the porous medium during the flooding operation. From the summary of data on the effectiveness of the gas phase after injection of one pore volume of water, it is apparent that the presence of free gas should have a beneficial effect on oil recovery by water flooding in most practical cases. It is also of interest to notice that the effectiveness of the gas appears to be greatest in the flooding of viscous oils.

In regard to applications of the concept of gas effectiveness, it is pointed out that:

1. For depleted reservoirs, use of the values of gas effectiveness presented in this paper implies gas repressuring prior to water flooding. It is furthermore assumed that the pressure level attained is sufficient to render the effects of gas compressibility and solubility negligible. The amount of additional oil recovery indicated by the values of gas effectiveness, then, is over and above that obtained by primary depletion followed by water flooding without repressuring.

2. The values of gas effectiveness may also be used to evaluate additional oil recovery attainable by drop-

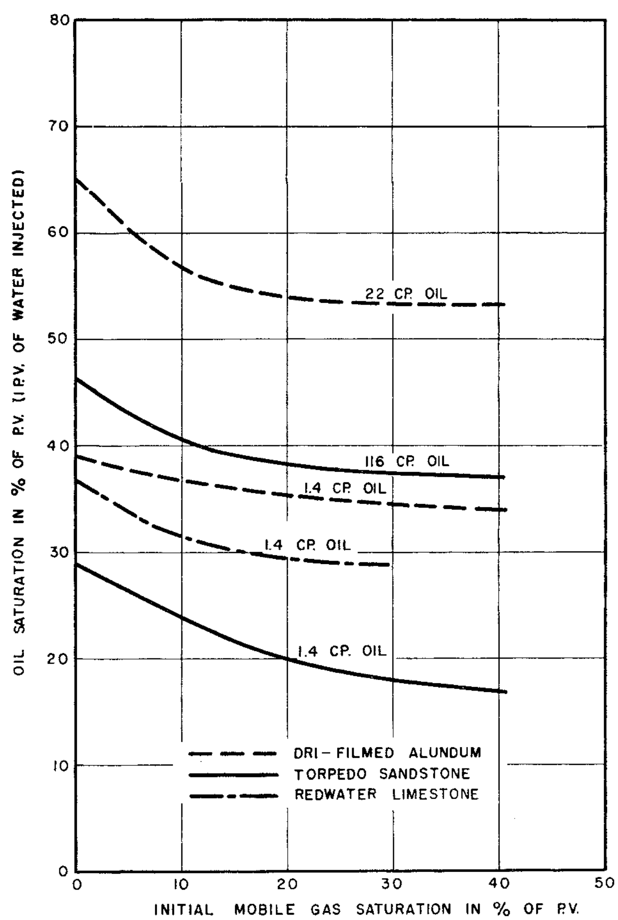

FIG. 7—RELATIONSHIPS BETWEEN INITIAL MOBILE GAS SATURATION AND RESIDUAL OIL SATURATION AFTER X 1 PV OF WATER INJECTION.

ping the pressure below the bubble point and creating a gas phase in high pressure reservoirs subjected to natural water drive or water flooding.

3. The values of gas effectiveness represent a measure of additional oil recovery in reservoir volumes. Determination of the additional oil recovery at stock tank conditions requires corrective evaluations accounting for the shrinkage or expansion of the oil at various operating stages.

4. In the case of water floods conducted after primary depletion and repressuring, the oil expansion and decrease in oil viscosity associated with the gas repressuring cause additional oil recoveries to be greater than indicated by the values of gas effectiveness. On the other hand, in the case of natural water drives, the shrinkage of the oil and increase in oil viscosity associated with the pressure decline required to create (or increase) the free gas phase, tend to counteract the beneficial effects caused by the presence of the gas.

Evaluation of Waterflood Behavior in the Presence of Free Gas from Short Core Tests

The performance of water floods in the presence of a mobile gas phase requires accurate measurements on three-phase flow systems. For short cores such measurements must be extremely precise because of the small quantities of fluids involved. However, in the light of the results of these studies, a less delicate experimental procedure can be employed. Such a procedure would consist of establishing first a trapped gas saturation by means of an oil flood, and then conducting a water flood in presence of this trapped gas. This approach, which eliminates the necessity of measuring three-phase production during a flooding test, permits the use of less complex equipment and is likely to yield more precise results on small core samples.

In order to check the validity of the data obtainable by means of the above procedure, water floods have been performed on a 2-in. dri-filmed Alundum core in the presence of an initially trapped gas phase. These floods correspond to Runs 41 through 44 in Table 2. The ratio of trapped to mobile gas, and the values of gas effectiveness determined with this short core were found to be in good agreement with the corresponding results obtained with the 12-in. dri-filmed Alundum core (Runs 31, 32, 38, and 39). These findings illustrate the feasibility of utilizing short core tests to determine the effect of free gas on waterflood behavior.

The proposed experimental procedure for short cores consists of conducting in succession two series of two-phase displacement tests resulting in two distinct sets of data: the relationship between mobile and trapped gas saturations on one hand (cf. Fig. 4), and the relationship between trapped gas saturation and residual oil saturation, on the other (cf. Figs. 5 and 6). Combination of these two relationships then allows correlation of the residual oil saturation with the mobile gas saturation existing at the initiation of the water flood, as illustrated by the curves of Fig. 7.

CONCLUSIONS

The present studies lead to the following conclusions:

1. The injection of water in a partly gas-saturated porous medium results in the formation of an oil bank which displaces part of the initial free gas phase, leaving behind a certain residual, trapped gas saturation. The oil filling up the pore space around this trapped gas saturation is then displaced in turn by the advancing water.

2. The residual oil saturations obtained by water flooding in the presence of a gas phase are appreciably lower than those obtained in the absence of gas. These reductions in residual saturation represent a measure of additional oil recovery over that obtained in a water flood where the gas phase is allowed to dissipate by compression and solution.

3. For a given porous medium and fluid system, there is a unique relationship between (a) the trapped gas saturation and the initial mobile gas saturation; (b) the oil saturation attainable at any one flooding stage and the trapped gas saturation existing in the porous medium during the flood; and (c) the oil saturation attainable at any one flooding stage and the initial mobile gas saturation. This latter relationship may be determined either by direct experimentation or by combination of the above relationships (a) and (b).

4. The use of simplified procedures in flooding tests on short core samples to evaluate the reduction in residual oil caused by the presence of a gas phase has been justified.

5. The results obtained in the present experimental studies are representative of the situation where the effects of gas compressibility and solubility are negligible. Practical applications to field conditions of the type of data described in these studies usually require corrective evaluations to account for the solubility and compressibility of the gas phase.

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