Influence of Propping Sand Wettability on Productivity of Hydraulically Fractured Oil Wells

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ABSTRACT

Of the many factors which affect the productivity of hydraulically fractured wells, the wettability of the propping sand has received little attention in the past. This paper shows that the wettability of the propping sand is an important factor which should not be overlooked.

An analysis of relative permeability data shows that fractures packed with water-wet sand should be more permeable to oil than are fractures packed with oil-wet sand. Laboratory results verify this conclusion. Calculations show that higher permeability to oil in the fracture should provide higher well productivity.

A method is presented which ensures that the propping sand in an induced fracture is water-wet even though oil is used as the fracturing fluid. The method has been used in more than 150 field jobs; the field results are discussed briefly.

The fluidized nature of water-wet sand in oil has given unexpected benefits. This characteristic of water-wet sand and how it has been used advantageously in field operations are discussed.

INTRODUCTION

Hydraulic fracturing of subsurface strata to increase the productivity of oil and gas wells has been practiced for about 10 years. Today, fracturing is used more often than any other method of well stimulation. Basically, the process consists of breaking down (fracturing) a subsurface formation with pressure applied by means of a carrier fluid, usually oil or water, and propping the induced fractures apart by means of an agent, usually sand, suspended in the carrier fluid. Currently about 68 per cent of all fracturing is done with a simple mixture of refined oil or lease crude oil and sand[1].

The research of other investigators has suggested that dry sand is rendered oil-wet when it is contracted with certain types of crude or refined oils.[2] Hence, it may be expected that some fracturing operations employing an oil as the carrier for sand leave fractures packed with oil-wet sand. Conversely, those operations which employ water as the carrier for the sand probably leave the fractures packed with water-wet sand. Since the permeability of a sand-packed fracture to a mixture of oil and water is dependent upon the wettability of the fracturing (frac) sand, research was undertaken to determine to what extent the wettability condition (water-wet or oil-wet) controls fracture permeability which, in turn, affects well productivity. Additional research was directed toward the development of a method for obtaining the desired fracture wettability.

In this report both theoretical and experimental evidence is presented to show the desirability of employing water-wet sand in fracturing operations. A method to obtain water-wet sand is discussed, and field results are reviewed briefly.

DEPENDENCE OF WELL PRODUCTIVITY ON FRACTURE WETTABILITY

To determine the dependence of well productivity on the wettability of the frac sand, it is necessary to know, first, the effect of fracture wettability on fracture permeability and, second, the effect of fracture permeability on well productivity. The relationship of these variables is considered separately in the order indicated.

EFFECT OF WETTABILITY ON PERMEABILITY

Fig. 1 shows relative permeability relations for 20-30 mesh Ottawa sand. Inspection of these curves reveals that the relative permeability to oil when a small amount of water accompanies the flow is considerably higher when water rather than oil is the wetting phase. For

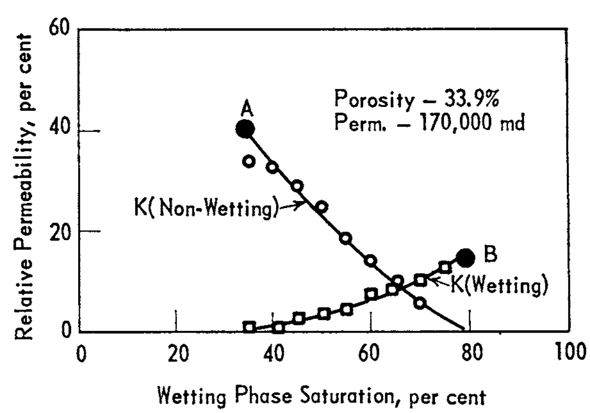

FIG. 1—RELATIVE PERMEABILITY CURVES OBTAINED BY WATER FLOODING A COLUMN PACKED WITH 20-30 MESH SAND.

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[1]References given at end of paper.

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example, compare the relative permeabilities at points A and B on the curves. At point A the relative permeability to oil is about 40 per cent of the single-fluid value when water is the wetting phase, but the relative permeability to oil at point B is about 15 per cent when oil is the wetting phase.

The degrees to which wettability influences oil permeability is seen more clearly if the relative permeability to oil is expressed as a function of the per cent of oil in the flowing stream. The following relation makes the transformation:

$$F_o = \frac{K_o/\mu_o}{K_o/\mu_o + K_w/\mu_w}$$

where

F_o = fraction of oil in the flowing stream,

F_w = fraction of water in the flowing stream,

K_o = relative permeability to oil,

K_w = relative permeability to water,

μ_o = viscosity of oil,

μ_w = viscosity of water.

The above equation was used to relate the relative permeability to oil to the fraction of oil in the produced stream for two wettability conditions, water-wet and oil-wet, and for viscosity ratios of 1, 10 and 60. Figs. 2 through 4 illustrate these results. These curves were obtained by using the data displayed in Fig. 1.

Fig. 2 shows that for an oil-water viscosity ratio of one:

1. The relative permeability to oil is greater when water is the wetting phase that when oil is the wetting phase if the oil in the produced fluid exceeds 50 per cent. For example, if water is the wetting phase and the flowing stream contains 3 per cent water (97 per cent oil in produced fluids), the permeability to oil is 33 per cent of the single-fluid value. On the other hand, if oil is the wetting phase, the permeability to oil is only 14 per cent of the single-fluid value. Thus, with 3 per cent water in the produced fluid, the water-wet condition gives an oil permeability 2.4 times greater than the oil-wet condition.

2. If the flowing stream contains less than 50 per cent oil, both wettability conditions give about the same oil permeability.

Figs. 3 and 4 show the effect of wettability on oil permeability when the oil-water viscosity ratios are 10 and 60. From these figures it can be seen that an increase in the viscosity ratio sharply increases the range of flowing stream compositions over which the water-wet condition is desirable.

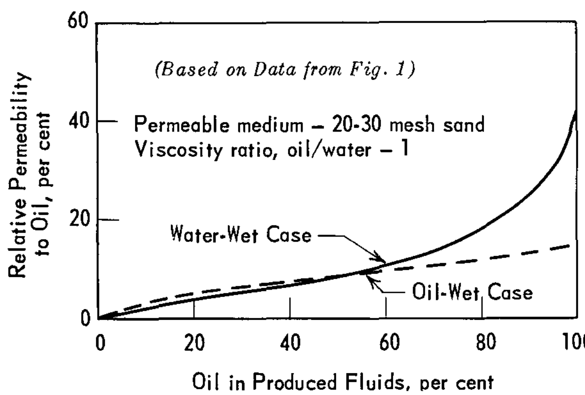

FIG. 2 — CALCULATED EFFECT OF WETTABILITY ON RELATIVE PERMEABILITY TO OIL.

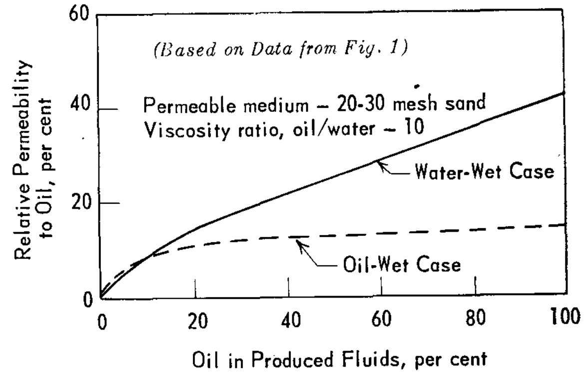

FIG. 3—CALCULATED EFFECT OF WETTABILITY ON RELATIVE PERMEABILITY TO OIL.

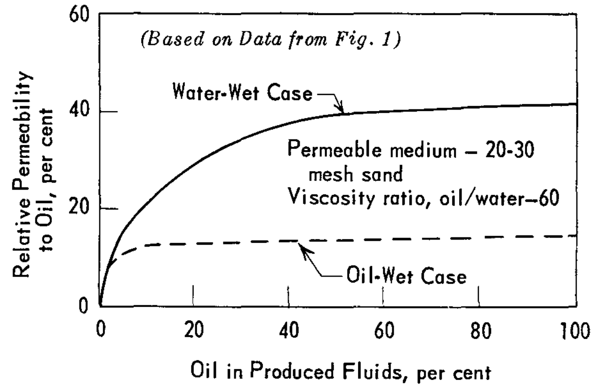

FIG. 4—CALCULATED EFFECT OF WETTABILITY ON RELATIVE PERMEABILITY TO OIL.

Although in many fields the oil-water viscosity ratio is close to one, there are some in which the ratio is much greater than one. For example, there are fields in which the oil-water viscosity ratio is 60 or greater. In such fields, oil-wet fractures reduce oil permeability for any stream composition.

The conclusion drawn from the above analysis suggests that water-wet frac sand gives better oil permeability than oil-wet sand. However, the analysis is based on relative permeability data obtained only under imbibition (waterflood) conditions with 20-30 mesh sand. The conditions that exist following a sand-in-oil fracturing operation suggest that imbibition relative permeability data should be employed to investigate the oil permeability of a fracture propped with water-wet sand, but drainage data should be used for the oil-wet case. The reasoning is as follows. If the sand were to remain water-wet while in the carrier oil, then a subsequent influx of water into the fracture would represent an increasing wetting phase, or imbibition-type condition. On the other hand, if the carrier (oil) makes the sand oil-wet, then an influx of water is accompanied by a decrease in the wetting phase (oil) saturation. This is referred to as a drainage condition. To provide data under conditions specifically encountered in fracturing operations, both drainage and imbibition relative permeability relations were obtained with 20-40 mesh round frac sand.

A copper tube, 153-cm long with an inside diameter of 1.1 cm, was packed with 20-40 mesh round frac sand. The column was saturated with water. Then, two constant-rate pumps — one delivering water and the other oil — were used in steady-state drainage per-

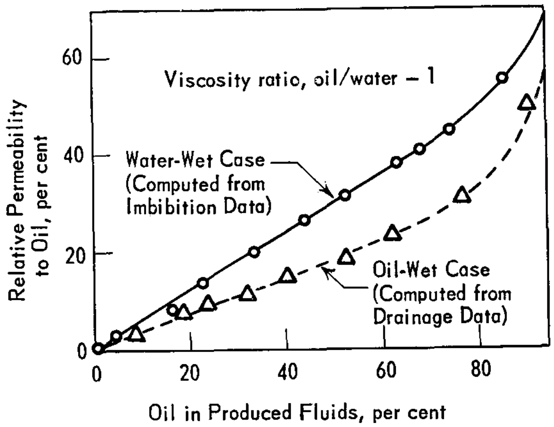

FIG. 5—EFFECT OF WETTABILITY ON RELATIVE PERMEABILITY TO OIL OF 20-40 MESH FRACTURE SAND.

meability experiments. After the data were obtained, the same arrangement was used in steady-state imbibition permeability experiments.

Fig. 5 shows the interpretation of the data. It is evident that the oil permeability is always greater when water is the wetting phase.

VERIFICATION OF PERMEABILITY BEHAVIOR IN OIL-WET AND WATER-WET SAND COLUMNS

The effect of wettability on permeability was investigated further by making four sets of permeability measurements on sand columns for both oil-wet and water-wet conditions. The results, which are discussed herein, physically demonstrated the validity of the conclusions drawn from relative permeability relations obtained with water-wet sand columns.

In the first set of measurements, 20-40 mesh frac sand packed into a Saran plastic tube, 91-cm long with an inside diameter of 0.10 cm, was saturated with crude oil. The packed tube was allowed to stand for 15 hours. This simulated the placement of sand in an oil that induces oil-wetness. Then, with two constant-rate pumps delivering an oil-water stream containing 10 per cent water, a measurement of the oil permeability was made. Immediately thereafter, the column was flushed with oil containing Agent A to render the sand water-wet. (For description of these agents, see Table 1.) The permeability measurements were made again with the same fluid stream. The oil permeability measured under the reinstated water-wet condition was 90 per cent greater than that measured under the oil-wet condition.

After the above measurements were completed, the small-diameter tube was cleaned and again packed with 20-40 mesh sand. The previous procedure was repeated to obtain a second set of measurements, this time with an oil-water stream containing 3 per cent water. In this case the oil permeability measured under the reinstated water-wet condition was 112 per cent greater than that measured under the oil-wet condition.

In a third test, a plastic tube, 392-cm long with an inside diameter of 0.38 cm was employed. The 20-40 mesh round frac sand was made oil-wet by flushing it with a 2 per cent solution of Agent B in distilled water. The constant-rate pumps were adjusted to deliver an oil-water stream containing 16 per cent water, and a measurement on the oil permeability was made. After this measurement was completed, the column was made water-wet by flushing it with 2 per cent Agent A in crude oil. Then, the permeability measurement was made again. The oil permeability measured under the reinstated water-wet condition was 34 per cent greater than that measured under the oil-wet condition.

To obtain the fourth set of data, the same column was used, and the pumps were adjusted to deliver an oil-water stream containing 7 per cent water. A measurement of the oil permeability was made, and the column was returned to the oil-wet condition through the use of the Agent B solution. Finally, a measurement of the oil permeability associated with this oil-wet condition was made. The oil permeability under the water-wet condition was 78 per cent greater than that under the oil-wet condition.

The results of these four experiments are summarized in Table 1. They show, for all the water-oil mixtures employed, that the relative permeability of the fracture sand to oil is greater when the sand is water-wet than it is when the sand is oil-wet.

EFFECT OF FRACTURE WETTABILITY ON WELL PRODUCTIVITY

When the effect of wettability on fracture permeability is known, it is possible to relate fracture wettability to well productivity through the use of information presented in a paper by van Poollen, *et al.*[4] The authors show that for both horizontal and vertical fractures well productivity is very dependent upon fracture permeability. In the summary of their paper, they conclude that, "Any method which causes a flow restriction within the propped fracture can appreciably reduce the possible production increase".

Now, the two effects—that of wettability on fracture permeability and that of fracture permeability on well productivity—can be combined to obtain the final effect of fracture wettability on well productivity. The result of this synthesis is given in Fig. 6. It shows for various formation permeabilities that production increases (to be expected after fracturing with oil-wet sand and after fracturing with water-wet sand). This analysis is based on the following assumptions:

1. The formation is strongly water-wet.
2. Formation thickness is 20 ft.
3. A very small amount of water (about 1 per cent of total production) accompanies the flow of oil, and the formation relative permeability to oil is 30 per cent of the single-fluid value.
4. The effect of fracture flow capacity on well productivity is as calculated by van Poollen, *et al,* and

TABLE 1 — RESULTS OF WETTABILITY EXPERIMENTS CONDUCTED WITH 20-40 MESH FRAC SAND

Experiment Number	Column Length (cm)	Column Diameter (cm)	Oil Wettability Induced With	Water Wettability Restored With	Water in Flowing Stream (per cent)	Increase in Oil Permeability Caused by Restoration of Water-Wetness (per cent)
1	91	0.10	Crude Oil	Agent A*	10	90
2	91	0.10	Crude Oil	Agent A*	3	112
3	392	0.38	Agent B**	Agent A*	16	34
4	392	0.38	Agent B**	Agent A*	7	78

*Agent A is a mixture of amine-neutralized anionic surfactants and non-ionic surfactants in a hydrocarbon base.
**Agent B is a mixture of primary amine acetates having the general formula, RNH_3COOCH_3, where R varies from 8 to 18 in even number increments.

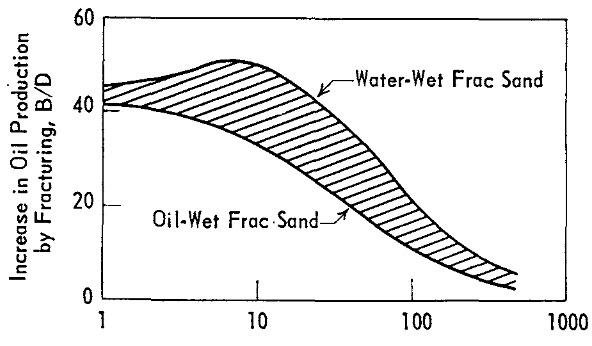

FIG. 6—CALCULATED EFFECT OF THE WETTABILITY OF THE PROPPING SAND ON THE PRODUCTIVITY OF HYDRAULICALLY FRACTURED OIL WELLS.

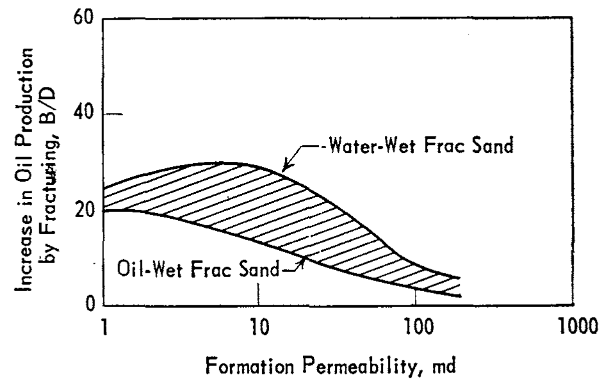

FIG. 7—CALCULATED EFFECT OF THE WETTABILITY OF THE PROPPING SAND ON THE PRODUCTIVITY OF HYDRAULICALLY FRACTURED OIL WELLS AFTER COMPACTION AND FORMATION "FINES" REDUCE THE PERMEABILITY OF THE FRACTURE.

shown in their Fig. A. This treatment considers a horizontal fracture.

5. 20-40 mesh round Ottawa frac sand is employed. The single-fluid permeability of this sand is 121 darcies.

6. Fracture width is ⅛ in.

7. For the water-oil ratio assumed in Assumption 3 and for oil-wet frac sand, the fracture permeability to oil is 20 darcies.

8. For the water-oil ratio in Assumption 3 and for water-wet frac sand, the fracture permeability to oil is 40 darcies; i.e., it is twice that of the oil-wet fracture.

9. Fracturing with oil-wet sand in every case yields a daily oil production of 50 B/D.

From Fig. 6 it is clear that water-wet frac sand is better than oil-wet frac sand.

After a fractured well has produced for a period of time, it may be expected that the fracture permeability will be reduced both by compaction of the frac sand and by the incorporation of formation fines with the frac sand. As this happens, the fracture permeability becomes even more sensitive to the frac sand wettability. Suppose, then, that assumptions 5, 7, 8 and 9 are modified to include these circumstances:

5a. Fracture contains a mixture of 20-40 mesh round frac sand and formations fines; the single-fluid permeability of the fracture is 60 darcies.

7a. For a low water-oil ratio and for oil-wet frac sand, the fracture permeability to oil is 10 darcies.

8a. For a low water-oil ratio and for water-wet frac sand, the fracture permeability to oil is 30 darcies; i.e., it is three times that of the fracture containing oil-wet sand. (An examination of typical relative permeability data shows that, in general, the sensitivity of porous rock to changes in wettability increases with decreasing permeability.)

9a. The fractured formation containing oil-wet frac sand in every case yields a daily oil production rate of 25 B/D.

Fig. 7 shows the calculated effect of fracture wettability on production increase after compaction and formation fines reduce fracture permeability and alter the relative permeability curves. These results indicate that the importance of having a completely water-wet fracture increases as the productivity of the well declines.

Since water-wet frac sand gives substantially higher well productivity than does oil-wet sand, it is important to know the wettability imparted to frac sand during the fracturing operations. The following section deals with this consideration.

WETTABILITY OF FRAC SAND

When water is used as the carrier in fracturing operations, the sand is probably strongly water-wet immediately after placement in the fracture. However, as was mentioned earlier, most fracturing operations employ sand-in-oil mixtures. To ascertain the likelihood of obtaining oil-wet fractures during sand-oil fracturing operations, a number of representative oils (both refined and crude) were tested for their ability to render sand oil-wet. The test procedure and results are discussed below. Also, the permanence of original wettability is discussed.

DETERMINATION OF WETTABILITY OF DRY SAND MIXED WITH VARIOUS OILS

A simple procedure was devised so that the wettability of dry sand might be determined after it is mixed with various oils. Clean, dry sand was mixed thoroughly with the oil. After the sand had settled for several hours into a relatively firm bed in the bottom of the beaker, the excess oil was decanted and tap water was poured gently upon the oil-saturated sand bed. The effect was observed to note whether the sand was water-wet or oil-wet. If the sand was water-wet, the water spontaneously displaced the oil from the sand.

These results are summaried in Table 2. All of the oils except one rendered dry sand oil-wet. This information indicates that fracturing operations in which dry sand is mixed directly with oil usually leave fractures packed with sand that is initially oil-wet.

PERMANENCE OF OIL-WETNESS

If fractures are packed with sand which is oil-wet, does the initial oil-wet condition persist? The wettability tests described herein indicated that under static conditions at atmospheric temperature, there is no

TABLE 2 — WETTABILITY IMPARTED TO DRY SAND BY VARIOUS OILS

Oil	Wettability Imparted to Dry Sand
1. Clean kerosene	Water-wet (W)
2. Kerosene stored in rubber bladder	Oil-wet (O)
3. Crude oil A	O
4. Crude oil B	O
5. Refined oil A	O
6. Crude oil C	W
7. Crude oil D	O
8. Crude oil D containing Visofrac additive	O
9. Crude oil D containing Petrogel additive	
10. Refined oil B	O
11. Crude oil E	O
12. Refined oil C	O
13. Crude oil F	O
14. Refined oil D	O
15. Refined oil E	O

tendency for reversion to the water-wet state. In similar tests conducted at 140°F for several days, the oil-wet condition persisted. It is believed that, after placement of oil-wet frac sand, continuous flow of oil and water through the sand does not alter the wettability, and therefore the frac sand retains its initial oil-wet condition.

Permanence of Water-Wetness

If a frac sand is water-wet immediately after placement in the fracture, it probably remains water-wet. This reasoning is substantiated by the fact that most sand reservoirs are decidedly water-wet and are believed to have been so through geologic time.

METHOD FOR OBTAINING WATER-WET FRAC SAND

The analysis of relative permeability data and the laboratory studies have shown that higher well productivity is obtained with water-wet sand than with oil-wet sand. From these considerations, water appears to be the best carrier fluid for hydraulic fracturing. However, there are many areas where oil is used almost exclusively as the sand carrier because problems might be caused by the use of water. Thus, it is desirable to have a method for imparting water-wetness to sand during a primary fracturing operation employing oil as the carrier. The following method has been perfected to render sand water-wet.

Water-Wetted Sand for Use in Sand-Oil Fracturing

In those fracturing operations requiring oil as the carrier, sand is wetted with water before it is dispersed into the oil. In this manner each sand grain is coated with a film of water which protects the sand surface from oil. Wet sand, however, is extremely difficult to disperse in oil because the sand grains are held together by water. To overcome this difficulty, an interfacial tension-reducing agent is added to the water. Laboratory investigation reveals that a number of surface active agents are satisfactory for the purpose of lowering the interfacial tension sufficiently to allow the wet sand to be blended smoothly in the oil. Among the agents found to be satisfactory are certain of the common household detergents. The detergent is mixed into the water prior to the addition of the sand. When the resulting wet sand is mixed into the oil, it forms a very fluid mixture, and the sand remains strongly water-wet.

FIELD EXPERIENCE WITH WATER-WET SAND

Fracturing with Water-Wet Sand

Humble has performed more than 150 fracturing operations with water-wet sand in an oil carrier.

The results indicate that use of water-wet sand is helpful in obtaining better fracturing results. For example, in one East Texas field, two wells were fractured with water-wet sand. The oil potentials immediately after fracturing were 57 B/D and 63 B/D, respectively, which are comparable with the best results obtained in any part of the field. Furthermore, the productivity of these wells had not declined five months after the fracturing treatments were performed.

In a North Texas field, two wells were fractured with water-wet sand. The results of these jobs together with the result of an oil-wet sand job in a comparable well are given in Table 3. From these data it is evident that much better results were obtained by the use of water-wet sand in Well B than those obtained by the use of oil-wet sand in Well C. The productivity resulting from the water-wet sand job in Well A was about the same as that obtained with oil-wet sand in Well C even though less sand was used on the water-wet sand job.

Gravel Packing with Water-Wet Sand

Another application for water-wet sand is in gravel-packing operations. This application is illustrated by the experience gained in gravel packing a well in Southeast Texas. A prior attempt to gravel pack this well conventionally was unsuccessful because of flow of formation sand into the wellbore before screen and liner could be set. The second gravel-pack job utilized water-wet sand. It was accomplished with the screen and liner in place, and a total of 10,000 lb of sand in 9,820 gal of 30-gravity lease crude oil was injected. The well produced 105 B/D with 6 per cent salt water, which is a relatively high productivity for this type of completion in this particular area.

Sand-Fluidity—An Additional Advantage

During the course of the field applications, an unexpected advantage of mixtures of water-wet sand and oil was discovered. It was found that the sand, if allowed to settle, did not form a compacted mass as is normally the case; rather, it settled into a fluid mass that flowed easily. This property of wet sand-oil mixtures has been verified in the laboratory. The following ways to take advantage of this property have been developed by field personnel.

MITIGATION OF SANDOUT DIFFICULTIES

In one fracturing operation conducted in an East Texas well, the pumping equipment failed when the wellbore was full of oil containing water-wet sand. Injection ceased for 45 minutes while the pump truck was being repaired. A sandout was anticipated but did not develop. After repair of the equipment, pumping was resumed, and the remainder of the sand was injected into the formation.

In another fracturing operation conducted in a West Texas well, a sandout was experienced after 27,000 lb of water-wet sand had been injected into the wellbore (down tubing and annulus). The treatment was stopped, the tubing was connected to a tank and 8,000 lb of sand was circulated out of the hole. The well was placed on production. It is believed that this well would have required an extensive clean-out operation had an ordinary, dry sand-in-oil job been performed.

In a fracturing job in a Texas Gulf Coast well, a sandout was encountered at the end of the first 5,000-gal stage of an attempted four-stage fracturing job.

TABLE 3—COMPARISON OF WATER-WET AND OIL-WET SAND FRACTURING IN COMPARABLE WELLS IN NORTH TEXAS FIELD

Well	Fracture Treatment	Production* (B/D) Fluid	Oil	Water	GOR (cu ft/bbl)	Perforations (ft)	Evaluation Factor (bbl fluid/day/ft of perforations)
A	5,000 gal 6,000 lb water-wet sand	79	64	15	451	10	7.9
B	5,000 gal 5,000 lb water-wet sand	208	208	Trace	353	15	13.9
C	10,000 gal 10,000 lb oil-wet sand	85	73	12	1108	10	8.5

*Approximately one month after initial completion and fracturing.

Attempts were made to reverse circulate the well, but the circulating device in the packer would not open. After four hours the circulating device was finally opened, and the concentrated water-wet sand and oil mixture remaining in the tubing was reverse-circulated without difficulty or excessive pump pressure. It is believed that this well, which is 10,000-ft deep, would also have acquired an expensive clean-out operation had an ordinary dry sand-in-oil job been performed.

PLACEMENT OF SAND WITH DUMP BAILER

In the placement of sand by the dump-bailer technique often the sand becomes packed in the dump bailer cannot be completely dislodged. It has been found that wetting the sand with the same solution normally used in water-wet sand fracturing operations eliminates this difficulty, and all of the sand in the dump bailer falls freely into the wellbore when the bailer release is actuated.

CONCLUSIONS

Theoretical considerations indicate that water-wet frac sand gives appreciably higher productivities in hydraulically fractured wells than does oil-wet sand. Laboratory studies confirm this conclusion.

Water-wet sand can be maintained in fracturing operations employing oil as the carrier by simply wetting the sand with water containing a small quantity of a suitable detergent prior to dispersing the sand in the oil.

Water-wet sand has been used in more than 150 fracturing jobs. In general, these jobs have resulted in well productivities higher than those which have been obtained in the past with the conventional sand-oil procedure.

The use of water-wet sand in sand-oil fracturing operations has the added advantage of providing a fluidized settled mass in case of sandouts or equipment failure. This fluidized settled mass, unlike compacted sand, can be easily removed by circulation. This permits less expensive, low-rate fracturing jobs to be conducted without the risk of incurring costly clean-out operations.

Placement of sand by dump bailer is facilitated by wetting the sand with a water solution of a suitable detergent.

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