Reservoir Productivity Can Be Improved By The Judicious Application Of Sweep Efficiency Principles

By DUANE A. CRAWFORD
Texas Technological College

INTRODUCTION

Of primary concern to the reservoir engineer is the prediction of recoverable oil from a reservoir subjected to a given recovery process. Fluid displacement theory dictates the displacement efficiency expected from a given drive, but this efficiency does not include the effect of flood front sweepout. If fluid could be injected into and produced along the full cross-sectional area of the reservoir perpindicular to the path of the fluids, then the fraction of recoverable oil could reasonably correspond to the displacement efficiency derived from theoretical calculations.

However, since the only practical means of injecting and extracting fluids from a reservoir is through wells, the natural consequence of flood front sweepout must be considered. This sweepout behavior greatly alters theoretical frontal displacement, and must be taken into account if a realistic picture of oil recovery is to be determined. Fig. 1 includes the flood front configurations for several well patterns.

It is the purpose of this paper to review the physical principles of sweepout behavior (sweep efficiency), show its relationship to the reservoir and associated fluid phenomena, and its use in determining oil recovery.

Sweep efficiency is that fraction or per cent of the pattern pore space traversed by the displacing fluid as compared to the pore volume of the total floodable pattern. In this sense, especially in the case of a homogeneous, isotropic reservoir, areal sweep efficiency and volumetric sweep efficiency are identical.

HISTORY

Early Analytical and Experimental Investigations

Because knowledge of sweep efficiency is necessary for predicting the recovery performance of a reservoir, the sweep concept has long attracted the attention of various investigators. Muskat first considered the problem by applying rigorous mathematical analyses to two-dimensional electrolytic (blotter) models and sheet-conduction models.[1, 2] He made use of the concept of equipotential lines, streamlines, fluid conductivities, and breakthrough sweep efficiencies for various well arrays. Muskat's work was applicable to defining breakthrough sweep efficiencies assuming a mobility ratio of one.

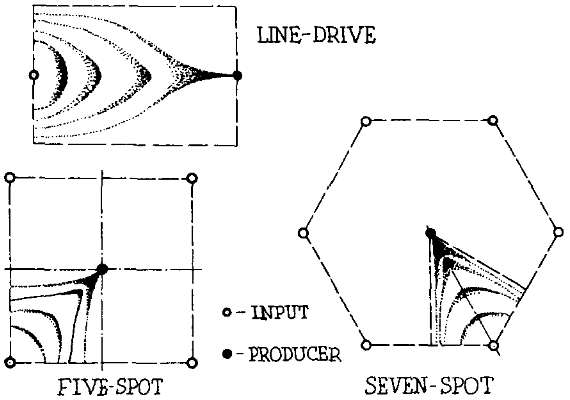

Fig. 1 Typical flood front configurations of representative patterns. Isotropic permeability and unity mobility ratio.

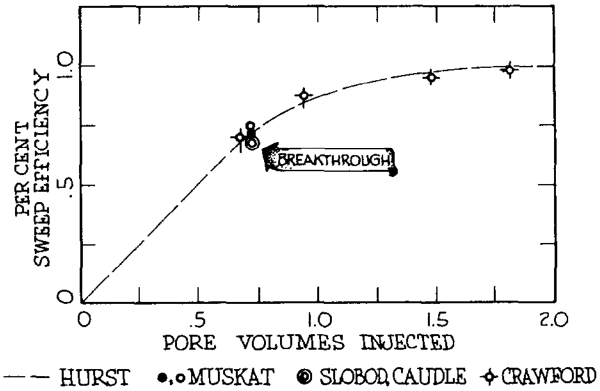

Fig. 2 Comparison of areal sweepout performance of the five-spot pattern by several investigators. (Reference 13)

Mobility ratio is the ratio of the displacing phase mobility to the displaced phase mobility. Mobility is the ratio of the relative permeability to the fluid viscosity of the fluid (SPE CONVENTION, M). In summary Muskat presented methods where mathematical analyses and model studies correlated to yield areal sweep efficiencies at breakthrough for various well patterns. Most important he devised expressions defining sweep efficiencies for basic flooding patterns under conditions of a mobility ratio of unity. Botset presented a potentiometric analysis of sweep efficiency that supplemented Muskat's work, showing that the method was limited to the study of incompressible fluids, of equal densities and viscosities, flowing into media displaying homogeneous permeability.[3, 4]

Hurst presented an analytical evaluation of the areal sweepout performance of the standard five-spot pattern by applying the La Place Transformation.[5] His results agreed closely with Muskat's determination of 72.3 per cent sweepout at breakthrough for a standard five-spot pattern. Hurst's main contribution was the mathematical prediction of the behavior of the sweep performance curve after breakthrough at a mobility ratio of unity. This is illustrated in Fig. 2 and listed in Table 1. This prediction was later verified by various experimental studies.

Prats later presented a similar mathematical analysis of breakthrough sweep efficiency of the staggered line-drive pattern; a special case is the five-spot pattern.[6] Thus, the door was opened for investigation of mobility ratio effects on sweep efficiency and the behavior of sweep efficiency after breakthrough. Cheek's results, obtained from fluid mapper studies, agreed closely with Muskat.[7]

TABLE 1
(Reference 13)

AREAL SWEEPOUT EFFICIENCIES FOR THE FIVE-SPOT AND SEVEN-SPOT PATTERNS AS OBSERVED AT DISPLACING PHASE BREAKTHROUGH

THE FIVE-SPOT PATTERN:

Investigator, Technique and Reference	Breakthrough Sweep Efficiency
Muskat, early electrolytic model, ref. 1,2	75.3 per cent
Muskat, early analytical method, ref. 2	72.3 per cent
Hurst, analytical method, ref. 5	72.6 per cent
Muskat, later analytical solution, ref. 2	71.5 per cent
Fay and Prats, numerical solution, ref. 10	73.0 per cent
Aronofsky, unpublished potentiometric results, ref. 10	70.0 per cent
Slobod and Caudle, X-Ray shadowgraph technique, ref. 10	69.0 per cent
Crawford, X-Ray shadowgraph technique, ref. 13	70 to 72 per cent

THE SEVEN-SPOT PATTERN:

Investigator, Technique and Reference	Breakthrough Sweep Efficiency
Muskat, analytical solution, ref. 1	74.0 per cent
Crawford, X-Ray shadowgraph technique, normal pattern, ref. 13	73.0 per cent
Crawford, X-Ray shadowgraph technique, inverted pattern, ref. 13	73.0 per cent

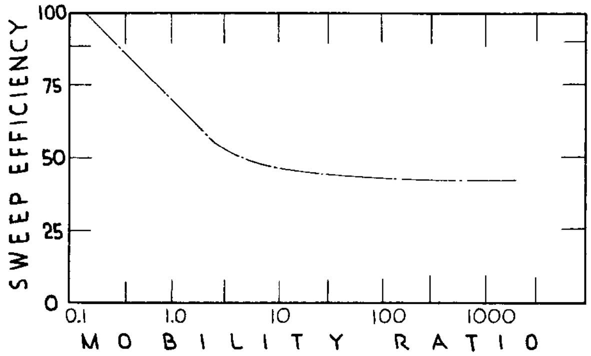

Fig. 3 Effect of mobility ratio (SPE convention) of injected and reservoir fluids on a pattern sweepout efficiency breakthrough in a five-spot system. After Caudle, reference 18.

Table 1 summarizes the breakthrough sweep efficiency determinations of these and other investigators.

Mobility Ratio Studies on Sweep Efficiency

Aronofsky presented both a numerical and potentiometric study of the direct line drive.[8] He advanced the importance of fluid mobility showing the variation of sweep efficiency with changes in mobility ratio. Morgan, Boyer, and Muskat presented one of the earliest examinations of models and cores using X-ray techniques for purposes of saturation determination.[9] This encouraged the application of X-ray shadowgraph techniques to areal sweepout performance.

Slobod and Caudle presented the X-ray shadowgraph technique in which scaled models (physical) were used to investigate sweepout factors for several types of spacing.[10] Slobod and Caudle's studies indicated that sweep efficiencies increased in value after breakthrough, as analytically predicted in Hurst's studies. Slobod and Caudle further postulated that under certain mobility ratio considerations additional fractions of oil could be swept from the reservoir. Caudle, Erickson, and Slobod, in their study of mobility ratio effects, concluded that as much as 90 per cent of the area outside the last row of wells, within a distance of one well spacing of the array, was ultimately contacted by the injection fluid for most water floods.[11]

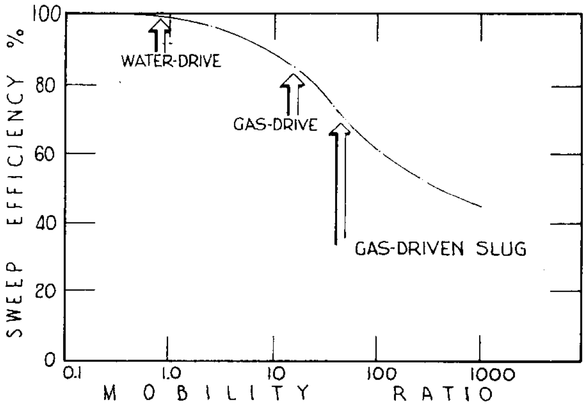

Fig. 4 Effect of mobility ratio (SPE convention) on pattern sweep efficiency of a five-spot when injection is continued past breakthrough. After Caudle, reference 18 and Kiescnnick, reference 19.

Dyes, Caudle and Erickson studied the effect of mobility ratios for several patterns over a wide mobility ratio range.[12] Their results are illustrated in Figs. 3 and 4. They concluded that as much as 50 per cent of the ultimate recovery could be obtained after breakthrough and that higher recoveries could be expected by more favorable mobility ratios (those values equal to or less than one). Crawford further justified these conclusions and also showed mobility ratio effects on the seven-spot pattern as shown in Fig. 5.[13]

Inhomogeneity Effects

Investigations up to this point either assumed or reasonably duplicated homogeneous reservoirs, especially with regard to permeability. Hutchinson opened investigation into reservoir inhomogeneity.[14] On a pore-to-pore basis his work indicated that a reservoir system may be uniform as far as one operation is concerned and not for another and that a carefully packed laboratory system is not truly uniform, especially with regard to an advancing flood front. On a reservoir basis, variation in lateral permeability may be so great that it affects the orientation of a well pattern and hence the sweepout behavior of the pattern.

With regard to stratification, Dyes and Braun noted that small errors in sweepout behavior are observed when mobility ratios approach unity.[15] When mobility ratios exceeded one, they noted that cross flow between strata was observed to improve performance with ratios less than one causing poorer performance.

They defined, for these studies, that mobility ratio was the ratio of the sum of the mobilities of all flowing phases ahead of the displacing phase divided by the sum of the mobilities of all flowing phases immediately behind that

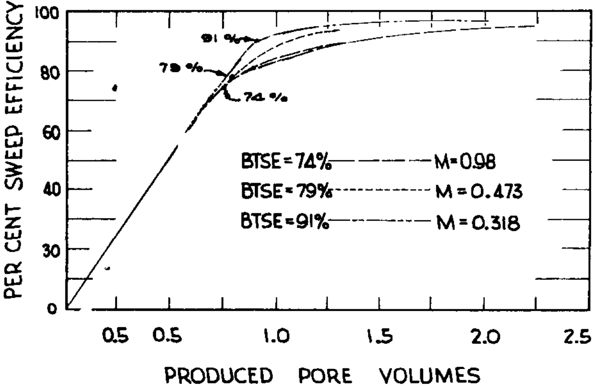

Fig. 5 Effect of favorable mobility ratios on the areal sweepout performance of a normal seven-spot pattern. After Crawford, reference 13.

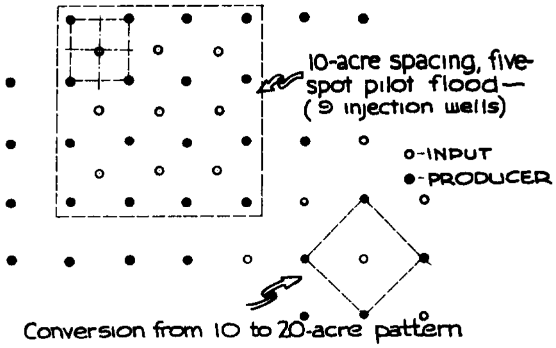

Fig. 6 Pilot flood area in the North Burbank, Osage County, Oklahoma Field. Pilot consisted of nine injection wells in a five-spot array. Reference 14

front (reciprocal definition to the SPE convention). Hutchinson pointed out that gravity, capillarity, and viscous forces contribute to crossflow by causing a vertical pressure gradient to exist through the permeability stratification.

Summary

It is concluded then that sweep efficiency is a direct indicator of expected oil recovery. It is further noted that sweep efficiency is affected by mobility ratio, stratification, and permeability variation. It should then be noted that any change in these variables will alter the quantity of oil recoverable from a given reservoir.

APPLICATION

Influence of Pattern Geometry

A decision as to the type of flooding pattern required for a reservoir of certain rock properties influences the amount of recovered oil. Muskat has shown breakthrough sweep efficiencies for the various patterns.[2] For the direct line drive this value ranges from 0.30 to 0.83 depending on the ratio of the distance between unlike wells (d) and the distance between like wells (a), as based on his formula: $E = 1 - (0.441)(d/a)$.

If these distances are equal, breakthrough sweep efficiency for the direct line drive pattern is approximately 55 per cent. For the staggered line drive pattern these breakthrough sweepout values range from 0.67 ($d/a = 0.5$) to 0.84 ($d/a = 4.0$) as based on his staggered line drive formulation. The special case of the staggered line drive when d/a is 0.5 corresponds to the familiar five-spot pattern and yields a breakthrough sweep efficiency of 0.72. For the seven-spot patterns, either normal or inverted, the breakthrough sweep efficiency is 0.74.[2, 13]

These sweepout values correspond with a mobility ratio of unity as compared to M 1.15 for a characteristic waterflood (SPE CONVENTION). The line drive patterns are often employed as crestal or peripheral systems because permeability-porosity pinchouts and reservoir geometry demand such patterns for successful exploitation. This pattern, for example, is used as a crestal line drive in the SACROC Unit, Snyder, Texas. For sand reservoirs of reasonably constant sand thickness, permeability and stratification, the five-spot pattern is often employed. However, if fluid conductivity is at a minimum (low permeability) it has often been advantageous to employ the seven-spot or "sun-flower" pattern such as found in the Loudon, Illinois waterflood. Obviously, as far as breakthrough recoveries are concerned, sweepouts between 30 and 74 per cent are obtainable depending on the pattern used.

Recoverable Oil At Breakthrough

In applying sweep efficiency concepts the most celebrated approach has been to incorporate breakthrough sweep efficiency values (Table 1) with the amount of displaceable oil in the pattern. As an example, consider a five-spot pattern spaced on a 660 foot spacing (10-acres) having an effective pay thickness of 20 feet, a formation volume factor of 1.2, a porosity of 15 per cent and an original oil saturation of 30 per cent. From frontal displacement theory it would be reasonable to expect 40 per cent of the original oil in place to be displaced by flood water, so that the recoverable oil would amount to

$$7758 \frac{\text{bbls.}}{\text{ac.-ft.}} \times Ah\phi \text{ ac.-ft.} \times Soi \times 0.40 \times 1/B =$$

$$(7758 \times 10 \times 20 \times 0.15 \times 0.80 \times 0.40)/1.2$$

62,060 barrels of stock tank oil. However, since only 72 per cent of the area of the pattern has been swept (Table 1) at breakthrough, the recovered oil expected would amount to only

$$62{,}060 \times 0.72 = 44.680 \text{ barrels of stock tank oil.}$$

This same system might be expected to recover as much as 75 per cent of the original oil in place, based on frontal advance theory, at a limiting water-oil ratio of 20 to 1, yielding a cumulative volume of recoverable oil equal to

$$7758 \times 10 \times 20 \times 0.15 \times 0.80 \times 0.75/1.2 = 116{,}370$$

barrels of stock tank oil. At the high water-oil ratio expected (20:1) for such a depletion, the swept portion of the reservoir could be as high as 85 per cent, hence

$$116{,}370 \times 0.85 = 98{,}900 \text{ barrels of stock tank oil}$$

could be recovered.

These calculations show why improvement in reservoir productivity should be forthcoming after water flood breakthrough if knowledge of the "scrubbing" effect of sweepout on untouched portions of the pattern is applied.

The Influence of Anisotropic Horizontal Permeability

It is most prudent to review the results of a pilot flood before developing, on a grand scale, an entire reservoir. Normally, a section of the field is selected that displays what is hoped to represent average rock and fluid properties for the reservoir.

The pilot area is drilled on a closer spacing so that a prepresentative reservoir performance might be observed in a reasonable length of time. Such a pilot flood was attempted in the North Burbank, Okla. field.[16, 17] A relatively large pilot program was undertaken due to the large size

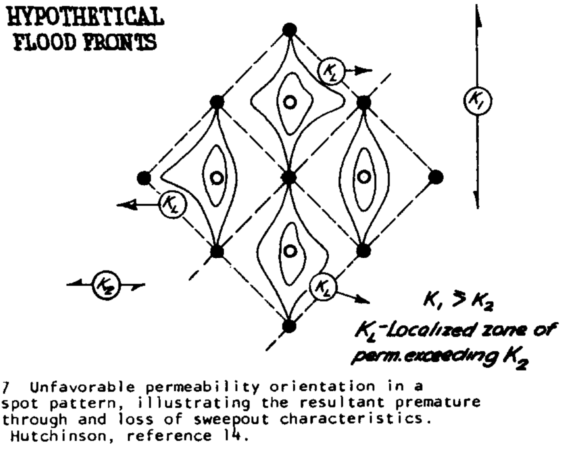

Fig. 7 Unfavorable permeability orientation in a five-spot pattern, illustrating the resultant premature breakthrough and loss of sweepout characteristics. After Hutchinson, reference 14.

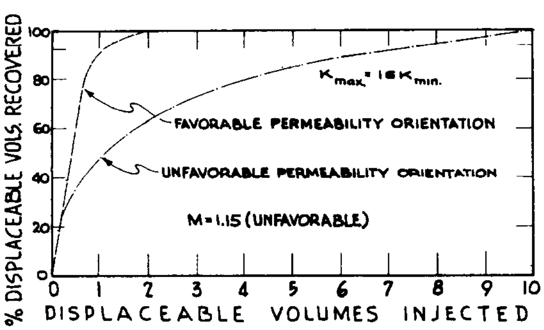

Fig. 8 Effect of permeability orientation on oil recovery in a five-spot pattern. After Hutchinson, reference 14.

of the reservoir, 20,000 acres. A 90 acre pilot program was selected, ultilizing a 10 acre per five-spot density, as shown in Fig. 6.

The performance of the pilot flood was excellent and a 1000 acre extension of the flood, on a 20 acre spacing, was authorized. The pilot flood was included in this extension by rotating the pattern 90 degrees to obtain the new spacing. This enlarged flood showed immediate signs of failure. Water injection rates declined rapidly and water breakthrough was premature. Fortunately the situation was remedied and the flood program became successful.

What caused such a failure? In the Burbank case it was the existence of anisotropic (lack of homogeneity) horizontal permeability. The North Burbank reservoir was found to contain a system of naturally oriented fractures running east and west. This resulted in the horizontal permeability of the reservoir to be greater in this east-west direction than in the north-south direction. The result was a more rapid advance of flood fronts in the east-west direction, yielding premature breakthrough and loss of sweep efficiency, as shown in Fig. 7.

Hutchinson has summarized laboratory studies with regard to the effect of permeability orientation on oil recovery.[14] This is graphically indicated in Fig. 8. In this work Hutchinson compared the five-spot production curves for both favorable (disalignment) and unfavorable (alignment of pattern, injection well to producing well, with high permeability) permeability orientation at an unfavorable mobility ratio (1.15). This mobility ratio of 1.15 is comparable to ratios found in most water floods. The pattern flooded with the most favorable orientation yielded much better displacement and sweep values.

What is the solution to this orientation problem? If anisotropic permeabilities do exist in a given reservoir, the difference between success and failure is reflected in the permeability orientation of the reservoir. If this permeability variation follows a general trend or trends, then the obvious solution is to shift the pattern to take advantage of this disconformity. This was done in the North Burbank waterflood with success. It is conceivable that flooding at 90 degrees to the high permeability trends would even improve sweep efficiency performance above textbook values.

How is this permeability variation detected? One method is to mark a compass card, mounted in a nonmagnetic sub, just before extraction of the core. This presupposes that the entire core is held securely in the core barrel. If true residual magnetism can be successfully determined for the core samples, then this means of orientation determination may be used. This method would be especially useful for reworking older cores. Much work has been devoted to this technique, but success is still elusive.

Dip meter surveys have been used to some advantage in determining permeability azimuth. This technique allows the dip of the formation and the dip in the core to be correlated. A severe disadvantage, in this method, would be correlating cores cut from horizontal formations. Another way of determining permeability inhomogeneity is to pilot flood a nine-spot pattern. After accounting for distance between wells and the time required for breakthrough to various wells, enough information is available to determine permeability ratio by the times required for breakthrough to occur. This method has the disadvantage of testing only the pilot flood portion of the reservoir.

It is interesting to note that the limited testing thus far reported indicates that vertical permeability variation and orientation corresponds directly with lateral permeability variation.[14] In most sands, the permeability ratio has been so low that it does not appreciably alter floodout performance. However, tests in fractured, solution channeled, and vugular formations, e. g. in west Texas, show appreciable permeability ratios. The average found by Hutchinson was 16 to 1. This would be expected. Fracture systems are usually the result of widespread stresses, capable of creating unidirectional permeability alterations.

Vugs and other solution channels are results of percolating ground waters which would be expected to follow a single path, usually down-dip. On the other hand, clastic sediments can approach sphericity in grain configuration and would be more expected to set up a pore pattern of quasi-equal permeability magnitude in all directions.

An interesting side light in defense of the need for core orientation is the fact that random plug cores may indicate stratification, but in reality are indicative only of permeability orientation.

Influence of Stratification

Tentative laboratory results indicate that the more favorable the mobility ratio (less than one) the more influence (cross-flow) stratification has on recovery. (Fig. 9) Whereas, for mobility ratios greater than one (unfavorable) reservoir performance can be calculated on the basis of noncommunicating sands. These effects become quite significant in the miscible slug process because favorable mobility ratios are encountered in this type of displacement system. In such a drive, the effects of stratification are noticed immediately.

Hutchinson has stated that in a two-layered system having vertical permeabilities differing by a factor of ten, that ten times as much solvent must be injected into the more permeable layer in order to place enough solvent into the less permeable layer. This becomes quite expensive. On the other hand, stratification has the advantage of overcoming gravity segregation in this communicating strata, thus improving areal sweep efficiency.

Miscible Drive Systems

Various investigators have pointed out the advantages of miscible systems. Capillary retention effects are removed, allowing more complete displacement of the

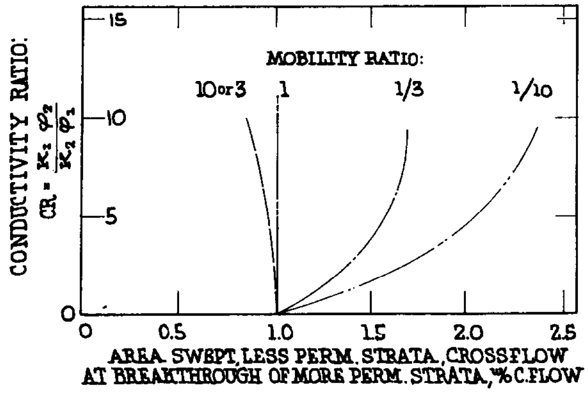

Fig. 9 Effect of cross flow in a two strata system as a function of conductivity ratio and mobility ratio. (Preliminary data after Hutchinson, reference 14)

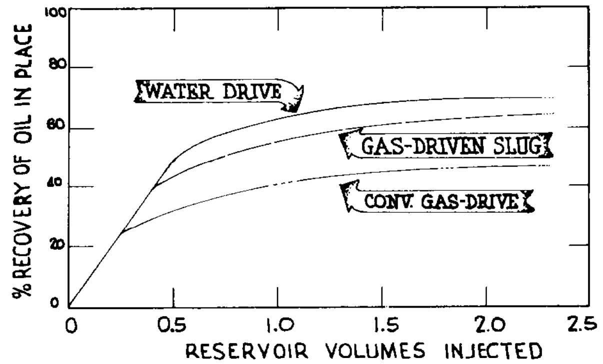

Fig. 10 Comparison of recoveries as a function of fluid volume in water-drive, gas drive, and conventional gas-drive systems. The varying per cents of recovery are due to the different mobility ratios encountered in the different processes. (References 18,19).

oil; also, more favorable mobility ratios become a reality, as in case of propane injection. However, Kieschnick has shown that gas driven miscible drives are less efficient than waterflood drives due to poor sweepout pattern efficiency.[19] This reduced sweep efficiency results from high values of mobility ratio (unfavorable), as summarized in Figs. 4 and 10. Kieschnick points out that in some cases, the cleaner displacement of the miscible systems often compensates for the detrimental effect of unfavorable mobility ratios.

Influence of Fractures

Dyes, Kemp and Caugle concluded that vertical and horizontal fractures, less than one-half the well spacing, could be used for five-spot patterns to increase productivity or injectivity without serious harm to sweepout efficiency.[20] Longer fractures did not harm sweepout provided the fracture was aligned with the producing well. However, it was noted that the throughput volume to attain a given recovery was increased, although ultimate recoveries were not seriously altered until fractures exceeded three-fourths the distance of well spacing.

They summarized their findings by indicating that conventional fracture treatments seem to achieve only short fracture systems. Consequently, the use of fracture to improve productivity and injectivity would not be expected to do harm to the sweepout behavior of the conventional flood. Operationally, the determination of fracture orientation would be the big problem.

CONCLUSIONS

Sweep efficiency is a naturally occuring measure of oil recovered from a reservoir encompassed by a given well geometry. It follows then, that proper adjustment of the variables that control sweepout performance will improve oil recovery from a given pattern. The type of well geometry employed in a given pattern greatly influences the amount of oil recoverable up to the time of breakthrough. This factor becomes less significant if injection is continued after breakthrough of the displacing phase occurs.

The most important single variable controlling sweep efficiency is the mobility ratio of the displacing and displaced phases moving in the reservoir. A favorable mobility ratio contributes to additional recovery, by virtue of increasing sweep efficiency per injected pore volume. An unfavorable mobility ratio tends to give poorer recovery values because sweep efficiency is reduced, especially by "fingering". This is true even in miscible systems.

It is also important to know the extent of areal sweepout at any stage of pattern depletion if a realistic picture of recoverable oil is to be obtained. Flood patterns should be oriented so that they will not flow with high permeability trends in the formation. The combined influence of mobility and stratification hamper the recovery of oil, especially when vertical permeability and favorable mobility ratios occur together.

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