DISPLACEMENT of OIL from POROUS MEDIA by MISCIBLE LIQUIDS

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ABSTRACT

The report describes scaled model experiments on the recovery of oil from porous sands by the injection of miscible liquids [solvents] and the subsequent recovery of the solvents by water flooding. Special attention has been paid to the scaling problem.

Scaling rules are deduced and their correctness is checked by carrying out experiments in tubes of various sizes.

Data are submitted on the effect of the viscosity ratio oil-solvent on the efficiency of the displacement process, the viscosity ratio varying from 1.5 to 5,000.

Breakthrough recoveries obtained when flooding with kerosene as a solvent, are equal to those obtained in water flooding at the same viscosity ratio, indicating that the phenomenon of viscous fingering is decisive. After breakthrough, however, flooding with a miscible liquid becomes much more efficient than a water flood and this is more pronounced as the viscosity ratio oil-solvent is higher.

Although high oil recoveries are obtained and most of the solvent in the sand can be recovered by a subsequent waterdrive, a straight flood with miscible liquids does not appear economically attractive because of the large quantities of solvent required. Therefore, a circulation process is introduced, the features of which are described in this paper. Though by means of this circulation process the amount of solvent required can be drastically reduced, the process is not yet economic.

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SCOPE OF THE INVESTIGATION

The recovery efficiency by water flood of oils of viscosities exceeding 50 cp is low. As interest in production of these highly viscous oils is growing at the moment, it was considered worthwhile to gain basic information on the feasibility of first flooding such oils with a low viscous miscible liquid [solvent] and subsequently producing the latter in a conventional way, e.g. by water flooding. The method has the obvious drawbacks that return on the investment is delayed until water flooding has begun and that it requires the investment of a more valuable product to produce a less valuable one. On the other hand, it may be expected that the displacement of one liquid by another is more efficient when the two liquids are miscible than when they are immiscible. As laboratory data on this point are scanty, the present investigation seemed justified.

Another argument for carrying out these experiments is that they present a valuable contribution to our concepts of the scaling problem in reservoir engineering studies. Some major difficulties which are encountered in the scaling of the waterflooding process such as the scaling of the capillary forces and the difficulty of obtaining the same permeability characteristics in the model do not present themselves in this case. As the fluids are miscible capillary forces do not play a role and as there is only one fluid phase, Darcy's law is valid in its original form. Consequently it is felt that the scaling rules can be deduced with a greater amount of certainty.

An essential feature of the experiments is that they are scaled model ones, which are, however, somewhat
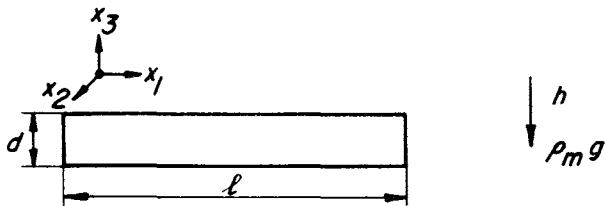
FIG. 1 — DIAGRAM ILLUSTRATING DIRECTION OF GRAVITATIONAL FORCE.

limited in scope in that they represent the rather ideal prototype of a homogeneous loose sand body completely saturated with a viscous oil that is subjected to a linear flood.

The experiments carried out can be divided into two groups:

1. Those carried out to obtain basic information on the displacement process only without considering any economic aspects. These experiments at the same time present a valuable contribution to our conceptions of the scaling problem in reservoir engineering studies.

2. Experiments in which the merits are evaluated of a procedure which aims at reducing the large amounts of solvent required in a straight flood for displacing the viscous oil. A recycling process is described in which the oil viscosity is gradually lowered until a viscosity level is obtained at which water flood can be successfully applied. In this way relatively small amounts of displacing miscible liquid may be sufficient. The cheapest displacing liquid will probably be a low viscous crude.

SCALING RULES

Experiments have been made in various horizontal cylindrical tubes [length l, diameter d], filled with sand of permeability k and completely saturated with oil of viscosity η_o. A miscible liquid [solvent] is injected at a constant rate of q at one end of the tube. The quantities of oil and solvent produced at the other end are measured.

Hydrodynamically our problem is governed by the equations of continuity and Darcy's law. If the oil is considered to be incompressible, the equation of continuity for it, taking diffusion of oil in solvent into account, may be written as:

$$- f \frac{\partial c_o}{\partial t} - \sum_i \frac{\partial}{\partial x_i} [c_o v_i] + f ED_o \sum_i \frac{\partial^2 c_o}{\partial x_i^2} = 0 \quad (1)$$

where $i = 1, 2, 3$.

Equation 1 obtains for an elementary cube, the dimensions of which are large compared to those of the pores. The v_i in the equation denotes a mean velocity component in a certain direction; in the pores, however, the direction of flow may be at angles to this mean flow direction. Thus the actual distance along which diffusion must occur is longer than in a non-porous medium. For this reason in the third term of Equation 1 the effective diffusion coefficient is indicated by ED_o, where D_o is the normal diffusion coefficient in a non-porous medium and E is a dimensionless factor which

will be smaller than one and which depends on the pore configuration.

Apart from this addition of the factors E and f, Equation 1 is identical to the equation of continuity for fluid flow in a non-porous medium. The factor f has been added to take into account that v_i is defined as the superficial velocity in accordance with reservoir engineering practice.

By substituting

$$x_i = X_i d \text{ and } t = T \frac{d^3}{q} \quad . \quad . \quad . \quad . \quad . \quad (2)$$

we can write the above equation in a dimensionless form:

$$- f \frac{\partial c_o}{\partial T} - \sum_i \frac{\partial}{\partial X_i} \left[\frac{c_o v_i d^2}{q} \right]$$

$$+ \frac{f ED_o d}{q} \sum_i \frac{\partial^2 c_o}{\partial X s_{12} + e + X_i^2} = 0 \quad . \quad . \quad . \quad (3)$$

A similar equation obtains for the solvent component, which can easily be found by replacing the index o in Equation 3 by s.

Also Darcy's law obtains

$$v_i = - \frac{k}{\eta_m} \left[\frac{\partial p}{\partial x_i} + \delta_i \rho_m g \right] . \quad . \quad . \quad . \quad (4)$$

where $i = 1, 2, 3$ and $\delta_1 = \delta_2 = 0$ and $\delta_3 = 1$ [Fig 1].

By introducing the same transformation (2), equation 4 can be written in a dimensionless form as follows:

$$\frac{v_i d^2}{q} = - \frac{\partial}{\partial X_i} \left[\frac{kpd}{q\eta_m} \right] - \delta_i \frac{\rho_m g k d^2}{q\eta_m} . \quad . \quad (5)$$

From equations 2, 3 and 5 it is seen that the following dimensionless products pertain to our problem:

a. independent variables: $\dfrac{x_i}{d}$ and $\dfrac{qt}{d^3}$

b. dependent variables: $\dfrac{v_i d^2}{q}$ and $\dfrac{kpd}{q\eta_m}$

c. coefficients: $\dfrac{\rho_m g k d^2}{q\eta_m}, \dfrac{q}{D_o d}, \dfrac{q}{D_s d}$

Instead of the last two coefficients we may also introduce one of them and the ratio of the two viz. D_o/D_s.

It should be noted that f, c_o, c_s and E are dimensionless. Consequently, they may be left out of the dimensionless products if we consider it as an obviously necessary condition that porosity, initial saturation and pore configuration are the same in model and prototype. If this is done and scaling is correct according to the dimensionless products derived, then c_o and c_s will have the same value at each scaled time and in each scaled point in model and prototype. If, f, C_o, C_g and E are not identical in model and prototype, they should be included in the dimensionless groups in the same way as the other parameters.

The following relations also hold:

$$c_s = 1 - c_o \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

$$\rho_m = c_o \rho_o + c_s \rho_s \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

$$\eta_m = \eta_m [c_o, \eta_o, \eta_s] \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

From equations 6 and 7 it follows that:

$$\frac{\rho_m}{\rho_o} = c_o + [1 - c_o] \frac{\rho_s}{\rho_o} \quad \cdots \quad (9)$$

Consequently ρ_m in $\dfrac{\rho_m g k d^2}{q \eta_m}$ may be replaced by ρ_o if the

group $\dfrac{\rho_s}{\rho_o}$ is introduced as c_o will nowhere differ from its

prototype value.

According to Equation 8 η_m can be written as

$$\eta_m = \Phi\left[\frac{\eta_o}{\eta_s}, \eta_s, c_o \right],$$ where Φ is some [complicated]

function. Therefore, in groups which contain η_m, it may be replaced by η_o if a new group η_o/η_s is introduced and η_s is taken equal to its value in practice, c_o being everywhere the same in prototype and model.

As the ratios η_o/η_s, ρ_o/ρ_s and D_o/D_s and in addition η_s must be the same in model and in prototype, *it is almost imperative to use the same liquids in both cases.*

One may wonder why the density of the mixture ρ_m can be replaced in the dimensionless group by ρ_o introducing only the ratio ρ_s/ρ_o, while η_m cannot be replaced by η_o without setting both the ratio η_o/η_s and η_s. The reason for this is that ρ_m/ρ_o is a function of ρ_s/ρ_o only, whereas such a simple relation does not exist between η_m/η_o and η_s/η_o.

The variables $\dfrac{v_i d^2}{q}$ cannot be easily be measured in our

experiments as it involves a determination of the flow velocity components in each point of the tube. However,

for the outflow end of the tube $\dfrac{v_i d^2}{q}$ can be transformed

into a more practical form. This is seen by multiplying

with the dimensionless factor $1/4\pi c_o$, giving $\dfrac{1/4\pi d^2 c_o v_i}{q}$.

The nominator of this group presents the oil produc-

tion per unit time [q_o]. Thus the variable $\dfrac{q_o}{q}$ has been in-

troduced, which is applied in its integrated form

$\dfrac{\int q_o dt}{\int q dt} = \dfrac{R}{Q}$ where R is the quantity of oil produced

and Q the total production [oil and solvent]. Both quantities are reported as percentages of the original amount of oil in place [= pore volume of the sand for an initial oil saturation of 100 per cent]. As oil and solvent are considered to be incompressible p can be replaced by Δp [pressure difference across the tube].

Consequently, the result of an experiment can be reported by giving the dependent variables R [recovery]

and $\dfrac{k \Delta pd}{q\eta_o}$ [dimensionless pressure number] as func-

tions of the independent variable $\dfrac{qt}{d^3}$ [dimensionless time

number]. Expressed in this way model and prototype should yield identical results, provided that the following dimensionless coefficients are the same:

$$\frac{q}{D_o d}, \quad \frac{\rho_o g k d^2}{q \eta_o}, \quad \frac{\eta_o}{\eta_s}, \quad \frac{\rho_o}{\rho_s}, \quad \frac{D_o}{D_s}$$

It will be clear that in order to have the same value

in model and prototype the independent variables $\dfrac{x}{d}$ require the geometrical similarity between model and prototype.

Assuming the linear dimensions of the model in which the same liquids are used as in the prototype, to be scaled down by a factor of a [$a > 1$] the first coefficient shows that q must be scaled down by the same factor, and the second coefficient shows that k must be scaled up by a. The dimensionless time number shows that t is scaled down by a^2, while from the pressure number it follows that Δp is scaled down by a.

It is therefore possible to satisfy the scaling rules when using the same liquids as in the prototype.

SCALED EXPERIMENTS WITH VARYING LINEAR DIMENSIONS

To check the correctness of the scaling conditions discussed in the preceding section, experiments in which all of the dimensionless coefficients had the same value have been made in cyclindrical tubes of different lengths. The lengths of the tubes were 1.03, 1.60 and 3.00 m; their diameters were chosen so as to give equal

$\dfrac{l}{d}$ ratios. The tubes were placed in a horizontal posi-

tion and were all fully saturated with the same oil of 0.3 N sec/m^2 [300 cp].*

The displacing liquid was kerosene, viscosity 1.2 x 10³ N sec/m^2 [1.2 cp]. The injection rates and the permea-

bilities were chosen in such a way that both $\dfrac{q}{d}$ and $k.d$

were [nearly] equal in all cases. It is easy to see that in that case also the dimensionless coefficients are [nearly] equal.

The values of q and k in the various experiments are given in Table 1.

The porosities of the sand were almost the same in the three cases [33 per cent to 36 per cent].

Fig. 2 shows the values of the dimensionless pressure

$\left[\dfrac{k \Delta pd}{q\eta_o} \right]$ and the recovery of the original oil in place [R]

plotted against the dimensionless time $\left[\dfrac{qt}{d^3} \right]$ for the three

cases. It appears that the curves for the two largest tubes coincide satisfactorily, but that those for the smallest tube show appreciable deviations. The reason for this may possibly be that the diameter of the 103-cm tube [6.4 cm] is too small as compared to the grain size of the sand [0.07 cm].

To apply these results to a practical case, let us assume a scaling factor $a = 100$ for the 3.00-m tube.

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*In the system used in this paper the units of mass, length, and time are kilogram, meter, and second, respectively. The corresponding unit of force is kg m/sec² called Newton (N).

1 N = 10^5 dyne; 1 N/m² = 10 dyne/cm² = 1.45 × 10^{-4} psi.
1 N sec/m² = 10 dyne sec/cm² = 10 poise.
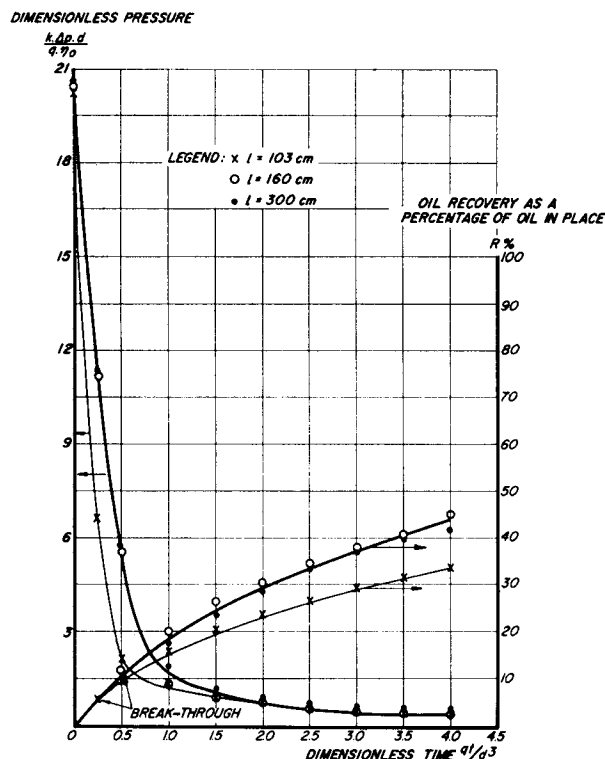1 m² = 1.013 × 10^{12} darcy.

FIG. 2 — DIMENSIONLESS PRESSURE NUMBER AND OIL RECOVERY AS A PERCENTAGE OF OIL ORIGINALLY IN PLACE VS DIMENSIONLESS TIME NUMBER FOR SCALED KEROSENE FLOODING EXPERIMENTS IN CYLINDRICAL TUBES.

The above results then obtain, for a linear flow in an oil sand of 300 m length, a thickness of 19 m, having a permeability of 750 md in which the injection rate is 17 m³/day. Breakthrough for this case will occur after about seven months.

From the figure it is seen that the pressure necessary to maintain the constant injection rate decreases very rapidly in the pre-breakthrough period. After that moment the decrease is far less pronounced.

EXPERIMENTS WITH VARYING VISCOSITY RATIO

According to results obtained by Croes and Schwarz[1] in water drive experiments, the viscosity ratio η_o/η_s can be expected to have a great effect on the recovery efficiency. To check this point, tests were carried out with η_o/η_s varying from 1.5 to 5,000. Again a kerosene viscosity 1.2 cp was used as the displacing fluid. In view of the results described above, these tests were made in the 1.60-m tube. To obtain a good comparison with the water drive experiments mentioned, the same sand having a permeability of 200×10^{-12} m² [200 D] and the same linear velocity [$v = 2.3 \times 10^{-4}$ m/sec corresponding to $q = 1.8 \times 10^{-6}$ m³/sec] were used. Results are given in Fig. 3 where the oil recovery is plotted against log η_o/η_s at different stages of production. As parameter for characterizing the production stage, the total production of oil and kerosene as a percentage of the pore volume (Q) is issued. The figure also shows some curves obtained in the waterdrive tests referred to above.
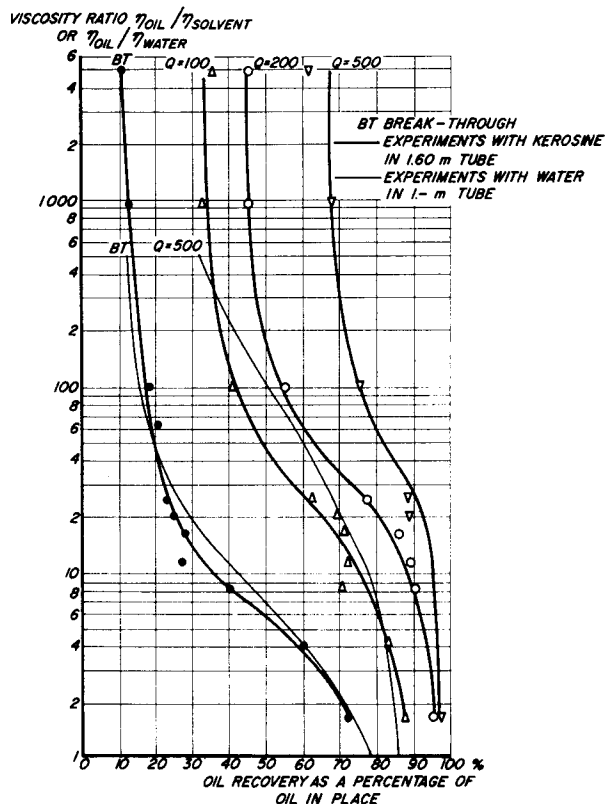
[1]References given at end of paper.

FIG. 3 — OIL RECOVERY WITH SOLVENT FLOODING, AS DEPENDENT ON THE VISCOSITY RATIO OF OIL AND SOLVENT COMPARED WITH OIL RECOVERY FROM WATER FLOODING TESTS ACCORDING TO CROES AND SCHWARZ. SOLVENT USED: KEROSENE, VISCOSITY 1.2 CP. CURVES ARE GIVEN FOR VARIOUS VALUES OF THE GROSS PRODUCTION Q [OIL + KEROSENE OR WATER] EXPRESSED AS A PERCENTAGE OF THE OIL ORIGINALLY IN PLACE.

It is seen that the breakthrough recoveries are nearly the same in both cases. Thus it is concluded that in this range the breakthrough recoveries are determined by the same phenomenon, namely, viscous fingering. After breakthrough of the displacing liquid, however, flooding with a miscible liquid becomes much more efficient than a water flood and this is the more pronounced as the viscosity ratio is higher. Apparently diffusion does not play an important role in the pre-breakthrough period, and can only make itself felt after prolonged flooding.

It has been claimed[2] that when displacing an oil by a miscible liquid a region exists in which the oil concentration increases gradually from zero to one in the direction of flow. The length of this transition zone is said to remain unaltered while it travels through the sand, thus acting as a plunger between the displacing and the displaced liquids. The length of this zone under field conditions is claimed to be of the order of 10 m, which is small compared to a well-distance of say 300 m.

As the results of the experiments in the two largest tubes tend to prove the correctness of the scaling rules, the length of the transition zone should consequently be of the order of 0.10 m for our 3.00-m tube. Accordingly a breakthrough recovery of the order of $\dfrac{300\text{-}10}{300}$

TABLE 2 — RESULTS OF FLOODING EXPERIMENTS WITH OIL AND
KEROSENE FOLLOWED UP BY A WATER DRIVE

η_o/η_s	Total amount of kerosene used in per cent of pore volume	Ultimate oil recovery after water flooding in per cent of pore volume	Amount of kerosene in per cent of pore volume left in sand pack after water flooding
24	650	95	15
103	650	82	10
925	650	77	11
4960	650	68	17

or 96 per cent should be expected. The breakthrough recoveries found in our experiments are much lower in the whole range of viscosity ratios investigated. As, moreover, flooding phenomena in the pre-breakthrough period appear to be similar to those in water-oil displacement tests where no plunger action exists, it is concluded that the assumption of a transition zone is not valid in displacements of oil by miscible fluids for the range of viscosity ratios larger than one.

After injection of an amount of kerosene of 6.5 times the pore volume, water was injected at the same rate. This produced a mixture of oil and kerosene, which, however, largely consisted of kerosene. Water flooding was continued until the water/oil mixture ratio equalled 20.

Results are shown in Table 2, where the produced quantity of viscous oil and the amount of kerosene left in the sand pack are given.

Evidently, high ultimate oil recoveries are obtained, also in the case of very viscous oils. Further, most of the solvent [kerosene] in the sand is recovered by the water flood.

However, a straight flood as applied in these experiments requires large quantities of solvent. A method by which to reduce these amounts, will be described below.

EXPERIMENTS WITH RECIRCULATION OF PRODUCED MIXTURE

When considering the results given in Table 2 it should be borne in mind that they were obtained after prolonged flooding with kerosene. Consequently, if we think of a commercial process, enormous amounts of kerosene would have to be injected, which afterwards would have to be separated again from the oil by distillation, thus rendering the whole process uneconomic.

In the flooding experiments described above it was found that after breakthrough the kerosene content of the mixture produced increases rapidly.

The economy of the process can therefore be improved by introducing the following procedure: After breakthrough of the solvent part of the outflow is reinjected, the remaining part is withdrawn from the circuit [bleeding] and replaced by the same amount of pure kerosene. This recycling process is continued until the viscosity of the resulting mixture in the sand has been lowered sufficiently for successful application of a water flood. Results of an experiment are given in Fig. 4.

Before breakthrough the outflow is homogeneous and its viscosity equals that of the original oil, then suddenly "schlieren" occur and the mean viscosity of the [inhomogeneous] outflow drops from 1.10 to 45 x 10⁻³ N sec/m² [1,100 cp to 45 cp]. Without recirculation this decrease in viscosity would continue; if, however, recirculation starts as in the test of Fig. 4, the viscosity of the outflow rises again owing to the increase in viscosity of the displacing fluid. Consequently, the viscosity
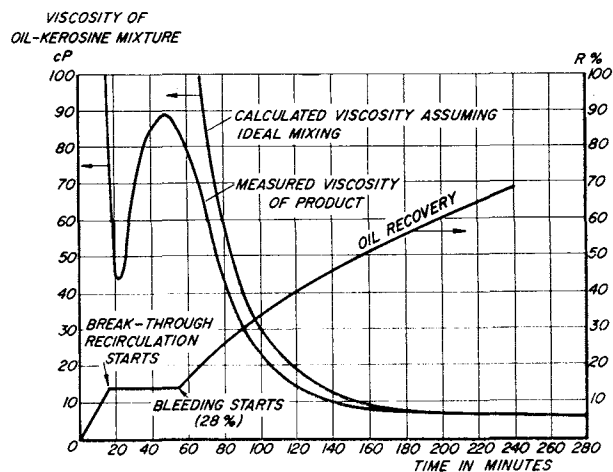

FIG. 4 — RESULTS OF A RECIRCULATION EXPERIMENT.

INITIAL OIL VISCOSITY 1100 cP
KEROSINE VISCOSITY 1.2 cP
BEFORE BREAK-THROUGH q = 37 ml/min.
AFTER BREAK-THROUGH q = 110 ml/min.

ratio of oil in place and displacing liquid will drop, which in its turn results in a more effective production of viscous oil.

As soon as bleeding is started and fresh kerosene is added to the inflow the viscosity of the outflow will again decrease rapidly. In Fig. 4 a curve is also drawn representing the viscosity of the mixture in the sand pack, calculated on the assumption that the pure kerosene injected is completely mixed up with the remaining original oil. It is seen that already after 170 minutes the two viscosity curves coincide, indicating that at that moment mixing was almost complete. Continuing recirculation would now become less effective as the viscosity drops only slowly and depends on the amount of fresh kerosene injected into the system. At this stage water drive should be started.

A series of experiments were carried out to study the influence of two variables, viz. the time of recirculation until bleeding starts and the fraction of the outflow which is continuously withdrawn from the circuit after bleeding has started.

From these experiments the following conclusions were drawn:

1. There is only a slight difference in results when bleeding started immediately after breakthrough and when it is started after 100 per cent PV has been recirculated. There is, however, a distinct influence of the degree of bleeding, less bleeding resulting in a markedly smaller amount of kerosene needed, without appreciably diminishing the ultimate recovery.

2. Water flooding should start as soon as possible, i.e., as soon as more or less homogeneous mixing of viscous oil and kerosene has been obtained. It is of interest to compare also the viscosity curves in Fig. 4, from which it is seen that as soon as 170 minutes after the beginning of the test practically homogeneous blending occurs.

3. The most salient fact, however, is that the economy of the procedure is much greater when applying recirculation.

From Table 2 it is seen that without recirculation 650 per cent PV of kerosene had to be used to reach an oil recovery of 77 per cent PV for a 1,100 cp oil,

while with recirculation a recovery of 81 per cent with only 48 per cent PV of kerosene could be obtained; the amount of kerosene lost was practically the same in both cases [11 per cent and 10 per cent respectively]. Yet the above figures show that to produce 100 m³ of a highly viscous oil 59 m³ of kerosene [or low viscous crude] must be used, of which 47 m³ can be recovered by distillation and 12 m³ are lost.

Though consequently the process may not be attractive for the moment it should be borne in mind, that the production of viscous oils will always involve extra costs. The process may further be of value for obtaining a bypass to start some other recovery process [underground combustion].

CONCLUSIONS

1. Model experiments on the displacement of oil by miscible liquid [solvent] should not be carried out on too small a scale. In the tests reported results with tubes of 1.60 and 3.00 m length were in good agreement, whereas those with a 1.03-m tube showed appreciable deviations.

2. Breakthrough recoveries obtained when flooding oils of different viscosities with kerosene as a solvent in unconsolidated sands are equal to those obtained in water flooding. When continuing the flooding process kerosene yields appreciably higher recoveries than water especially in the case of higher viscous oils. The drawback of a "straight" kerosene flood is, however, that large quantities of this solvent are required.

3. By applying a procedure in which after breakthrough the outflowing liquid is recirculated for some time, the amount of kerosene required can be drastically reduced without decreasing the oil recoveries. Though the procedure may be a potential bypass to start some other recovery process it is not yet an economic proposition.

ACKNOWLEDGMENT

NOMENCLATURE

f = porosity
$c_o, [c_s]$ = concentration of oil [solvent] in the mixture oil-solvent [m³/m³]
$\eta_o, [\eta_s] [\eta_m]$ = viscosity of oil, [solvent] [mixture] [N sec/m²]
$\rho_o, [\rho_s] [\rho_m]$ = density of [oil], [solvent], [mixture] [kg/m³]
$D_o, [D_s]$ = diffusion coefficient of oil [solvent] into solvent [oil] [m²/sec]
E = ratio of diffusion coefficient in a porous medium and the normal diffusion coefficient in a non porous medium
k = one-phase permeability [m²]
x_1, x_2, x_3 = Cartesian coordinates
X_1, X_2, X_3 = dimensionless coordinates
l = length parallel to flow direction [m]
d = length perpendicular to flow direction [m]
t = time [sec]
T = dimensionless time
q = flow rate [m³/sec]
g = acceleration of gravity [m/sec²]
p = pressure [N/m²]
Δp = pressure difference [N/m²]
v_1, v_2, v_3 = components of flow velocity [m/sec]
R = oil recovery as a percentage of original oil in place
Q = cumulative production [oil and solvent] as a percentage of original oil in place

REFERENCES

1. Croes, G. A., and Schwarz, N.: "Dimensionally Scaled Experiments and the Theories of the Water-Drive Process," Paper 332-G, Presented at the Petroleum Branch, AIME, Fall Meeting [October 1953], Dallas, Tex.

2. Morse, R. A.: [Stanolind Oil and Gas Co.] "Recovery of Oil from Reservoirs," German patent No. 849534 [July 1952].

DISCUSSION

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The authors conclude that in a miscible fluid drive in the range of viscosity ratios larger than one, there is no transition zone formed separating the injected and in-place fluids. This conclusion is based on the results of scale experiments in which a large prototype is studied by means of a small model. Our opposite conclusion has been reached based on laboratory tests on long core systems, flooded at oil field rates. Thus no scaling down of either time or distance is involved.

In core systems up to 100 ft in length, a more viscous oil was driven with a less viscous hydrocarbon (solvent). It was found that a transition zone was formed, which separates the in-place oil from the solvent. This zone was observed to grow rapidly at first, then gradually the rate of growth fell off to where it became nearly stabilized. As an example, in a 100-ft core system in which a 1.2 cps viscosity oil was pushed at a rate of advance of 2 ft per day by a solvent having 0.24 cps viscosity (viscosity ratio = 5), the transition zone was 5 ft long after traveling 10 ft, but after traveling 100 ft the zone was only about 10 ft long. The length of this zone was found to be influenced by its rate of advance, distance traveled, but most of all by the viscosity ratio and absolute viscosity of the fluids. Permeability of the porous material was found to have only a small effect on the length of the transition zone. Tests were run in an unconsolidated core system (2 darcys) and two consolidated core systems (400 md and 12 md).

It is a possibility that the work of the authors' is a study of the initiating stage of development of the transition zone. Our experience agrees with that of the authors for this phase of miscible fluid displacement in that the behavior during the initial phase is similar to immiscible fluid displacement. The scaling criteria that were used apparently are not complete enough to include the factors which control the formation of a transition zone.

AUTHORS' REPLY to R. A. MORSE

R. A. Morse's experiments are very valuable, especially as they are carried out in such very long cores.

There seems to be, however, an explanation which agrees with both our and his experimental results. In a cylindrical core with laminar flow in the longitudinal direction, diffusion has two effects. In the longitudinal direction it prevents the formation of a clear interface; in the radial direction, however, it helps in removing the original liquid which is trapped between "fingers" of the solvent. This promotes the formation of a more-or-less clear interface or transition zone. In the present case longitudinal diffusion can be safely neglected with respect to the large convection in that direction.

Consequently, the results we get will largely depend on whether the time which is required for diffusion to reduce radial variations of concentration to a negligible amount is small or large compared to the time necessary for longitudinal transport to produce such variations or fingers. This viscous fingering is likely to be especially important for high viscosity contrasts. Once fingers have been formed, some of them may grow rapidly to large dimensions until they are either confined by the boundaries of the reservoir or by other fingers. Thus, we believe the lateral dimensions of the fingers will be greater, the greater the width of the reservoir. Spreading out the finger boundary within which the concentration variation occurs must proceed by radial diffusion. Thus, the time required to eliminate the fingers will be proportional to d^2/D_o where d is diameter of the tube and D_o is the diffusion coefficient. Also, the time to produce a finger will be proportional to L/v where v is linear velocity and L the length the displacing fluid has traveled along the tube. The governing dimensionless group is consequently d^2v/D_oL. If this number is small, radial diffusion is relatively important and promotes the formation of a transition zone within which there is little or no radial variation in concentration. If it is large, diffusion will not play a signif-

icant role; and the effect achieved equals that obtained with immiscible liquids, i.e., viscous fingering.

Now, in Morse's experiment the values of v, D_o, and L are of the same order of magnitude as those in the field, but the lateral dimension d is greatly reduced as he uses a core, and this decreases the magnitude of the dimensionless number. Consequently, after traveling some length through the core a transition zone as described can develop. This, however, would not occur in the field where d is much larger and lateral diffusion cannot make itself felt over such a large distance in the time available. In the long core experiment the longitudinal distance is not scaled down, but the lateral distance is scaled down by a large factor. By giving both d/l and q/D_od the values occurring in the field, we gave also the number d^2v/D_oL the right value $(q = \frac{1}{4}\pi d^2v)$.

This also explains why in the initiating stage Morse's results agree with those given in the paper. The length L over which the fluid is displaced is still very short and the number d^2v/D_oL has still a low value; radial diffusion has not yet had time to make itself felt, and radial variations in concentrations or fingers still exist. Or, in other words, the ratio d/L still complies with that used by us.

In the later stage of Morse's experiment radial variations in concentrations are negligible, and there results a continuous concentration variation in longitudinal direction forming a transition zone between pure solvent and pure oil. Such a transition zone has a stabilizing effect in that it will prevent further viscous fingering. Viscous fingering can only be expected if there exists a large contrast in viscosity between two adjacent fluids, and this condition only occurs at the start of Morse's experiment.

It is, however, exactly that initiating stage which will occur in the field, and the stabilizing transition zone will not get time to develop before breakthrough to the production well occurs. ★★★