EFFECT OF STRATIFICATION ON RELATIVE PERMEABILITY

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INTRODUCTION

Although the oil industry has been aware of the directional variability of permeability in porous rock, the directional variability of relative permeability has been largely ignored. Yet it is apparent that such an effect must be present in a system in which the distribution of oil and gas within the porous matrix is controlled by capillary forces.

It is easy to visualize a rock composed of layers of fine and coarse material such that gas flow across the bedding planes would take place only after the average oil saturation had been reduced to a very low value. The fine layers, because of their greater capillarity, would remain saturated and act as barriers to the flow of gas after the coarse layers had been desaturated. Flow of gas parallel to the bedding planes would obviously take place at a much greater liquid saturation.

Without more complete information concerning the geology of a reservoir than is generally available, it is not possible to predict exactly how such phenomena would affect the over-all performance of an oil field. It is possible, however, to predict qualitatively the effect of stratification on relative permeability measurements made on laboratory cores.

In this investigation the effect of stratification was studied analytically by assuming that two porous materials with different capillary pressure-desaturation curves (but identical relative permeability curves) were in contact and in capillary equilibrium. As a qualitative check on the analytical results, cores having various degrees of visible stratification were used for relative permeability measurements made with fluids flowing both parallel and perpendicular to the bedding planes. A quantitative check was considered impractical because of the difficulty of devising models in which two materials of predetermined properties could be joined without the plane of contact becoming a discontinuity.

THEORETICAL CONSIDERATIONS AND ASSUMPTIONS

The assumption of capillary equilibrium in an oil-gas system implies that the difference in pressure between oil and gas is everywhere the same. This means that the curvature of the interfaces must be everywhere the same in order to satisfy the equation

$$P_c = \gamma \left(\frac{1}{r_1} + \frac{1}{r_2} \right) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where P_c is the pressure difference between phases, γ the interfacial tension and r_1 and r_2 are the major and minor radii of curvature. Depending on the pore size distribution of coarse and fine layers, the volumetric percentages of oil and gas in these layers will differ when equilibrium exists. The exact relationship can only be determined by obtaining the complete capillary pressure-desaturation curves for each of the porous materials in contact.

It has been pointed out elsewhere[1] that the capillary pressure-desaturation curves of sedimentary porous materials can often be approximated by the relation

$$\frac{1}{P_c^2} = C\, S_{oe} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where C is a constant and S_{oe} is the effective saturation to oil based on a percentage of the pore volume effective to flow. In the same paper it was indicated that, as a first approximation, the values of oil relative permeability are given by

$$K_{ro} = S_{oe}^4 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

and the values of gas relative permeability by

$$K_{rg} = (1 - S_{oe})^2 (1 - S_{oe}^2) \quad . \quad . \quad . \quad . \quad . \quad (4)$$

For this analysis Eqs. 2, 3, and 4 were assumed to apply to each of two components of a hypothetical porous rock in capillary equilibrium. It was also assumed that each of the components had a residual wetting phase saturation of 20 per cent so that 80 per cent of the total pore volume was effective to flow. The permeability of the coarse stratum was taken as 100, and its displacement pressure was such that C in Eq. 2 had the numerical value of 1. The corresponding values for the fine stratum were 10 for the permeability and 10 for C. Units are not specified because they do not enter into the final results. The choice of the permeabilities and displacement pressure ratios was made to expedite the calculations. Any reasonable rock properties could have been chosen without changing the results qualitatively.

Several arrangements of the two components were studied. Table 1 summarizes the resultant permeabilities obtained for four types of arrangement.

RELATIVE PERMEABILITY CALCULATIONS

The first step in the computation of relative permeability for the composite cores was the plotting of the capillary pressure-desaturation curves and the relative permeability curves for the individual components according to Eqs. 2, 3, and 4. At arbitrary

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[1] References given at end of paper.

values of P_c, corresponding values of saturation and relative permeability were obtained from these plots. Armed with these saturations for each component, the composite saturations of the four hypothetical cores were determined. The corresponding resultant permeabilities were given by the equations in the preceding table and, from these, the relative permeabilities were computed.

The results are shown in Figs. 1 and 2. Perhaps the most conspicuous effect of component orientation is the variation in critical gas saturation. For the series arrangements the critical gas saturations are 35 per cent when the components are equally divided and 65 per cent when the coarse components represent 90 per cent of the pore volume. Obviously, the thinner the stratum of fine material the greater will be the critical gas saturation. For the parallel arrangements the corresponding critical gas saturations are zero according to the assumptions made, i.e., if $S_{oe} = 1$ when $S_o = 1$, then Eq. 4 reduces to $K_{rg} = 0$ at $S_o = 1$. The gas relative permeability increases much more rapidly in the region of high liquid saturation when the coarse component comprises only 10 per cent of the pore volume of the composite core.

Another obvious feature of the figures is the inflections which occur in the curves for the parallel arrangements. The inflections correspond to the saturation at which the fine material first begins to desaturate. With the series arrangements the oil relative permeability curve drops slowly at high oil saturations, but eventually falls to a much lower value than is the case for the parallel arrangement. The coarse stratum, when desaturated, obstructs the flow of oil.

TABLE 1—PERMEABILITIES FOR FOUR TYPES OF ARRANGEMENTS

Volume Distribution Per Cent $k_1 = 100$	Volume Distribution Per Cent $k_2 = 10$	Type Arrangement	Resultant Permeability
50	50	Series	$k = \frac{2k_1k_2}{k_1 + k_2} = 18.2$
50	50	Parallel	$k = \frac{k_1 + k_2}{2} = 55.0$
90	10	Series	$k = \frac{10\ k_1k_2}{9\ k_2 + k_1} = 52.6$
10	90	Parallel	$k = \frac{k_1 + 9\ k_2}{10} = 19.0$

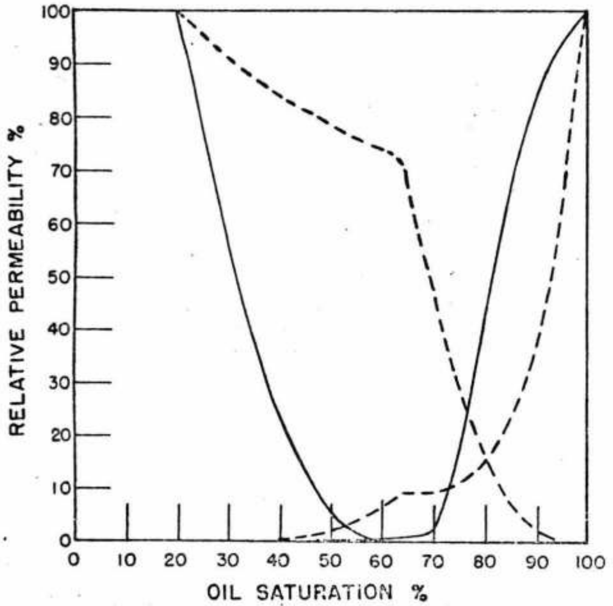

FIG. 1—RELATIVE PERMEABILITY COMPUTED FOR COMPOSITE CORES WITH EACH COMPONENT EQUAL 50 PER CENT OF CORE VOLUME.

———— Components in series
- - - - - - Components in parallel

MEASUREMENTS ON RESERVOIR CORES

It would not be expected that the computed curves discussed above would apply in detail to any natural core. Nevertheless, the qualitative characteristics of the computed curves have been observed frequently when making measurements on reservoir cores. Indeed these observations prompted the analytic study. An example of relative permeability measurements on a well consolidated core with flow parallel to obvious stratifications is presented in Fig. 3. Inflections are apparent in both the oil and gas relative permeability curves, indicating

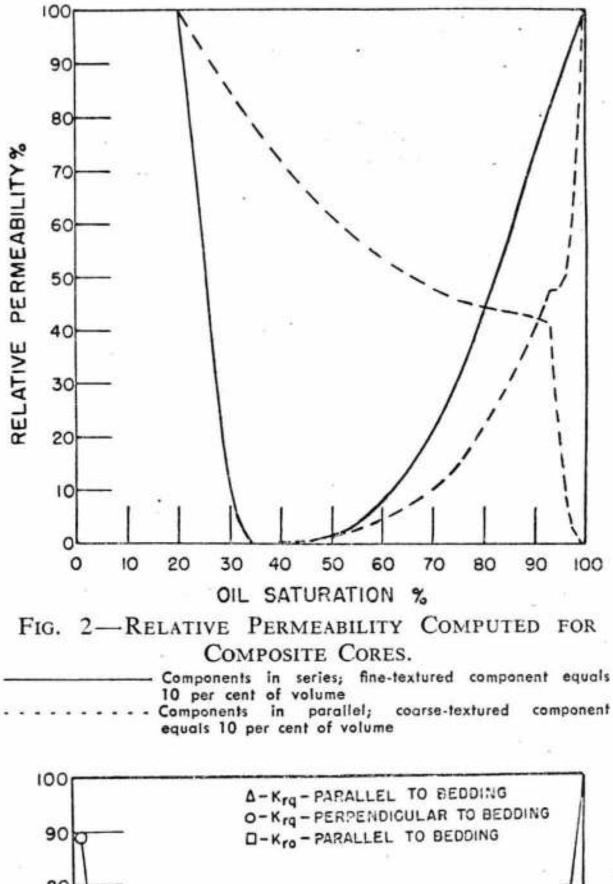

FIG. 2—RELATIVE PERMEABILITY COMPUTED FOR COMPOSITE CORES.

———— Components in series; fine-textured component equals 10 per cent of volume
- - - - - - Components in parallel; coarse-textured component equals 10 per cent of volume

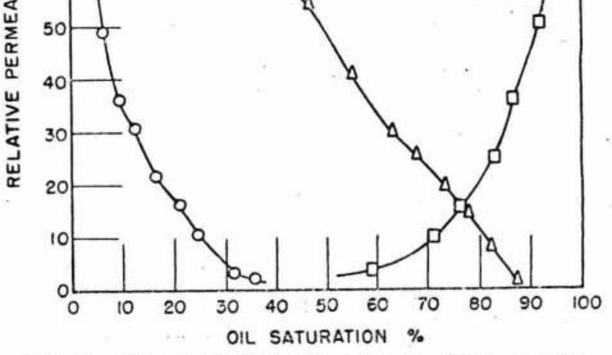

FIG. 3—RELATIVE PERMEABILITY OF ANISOTROPIC SANDSTONE.

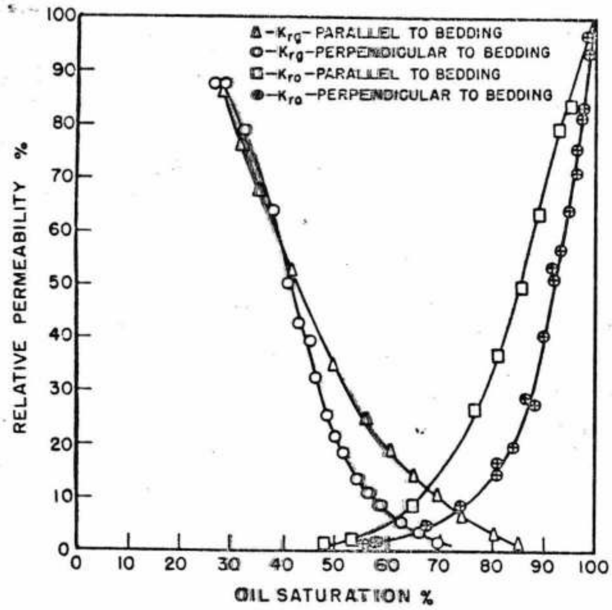

FIG. 4—DIRECTIONAL EFFECT ON RELATIVE PERMEABILITY OF BEREA SANDSTONE.

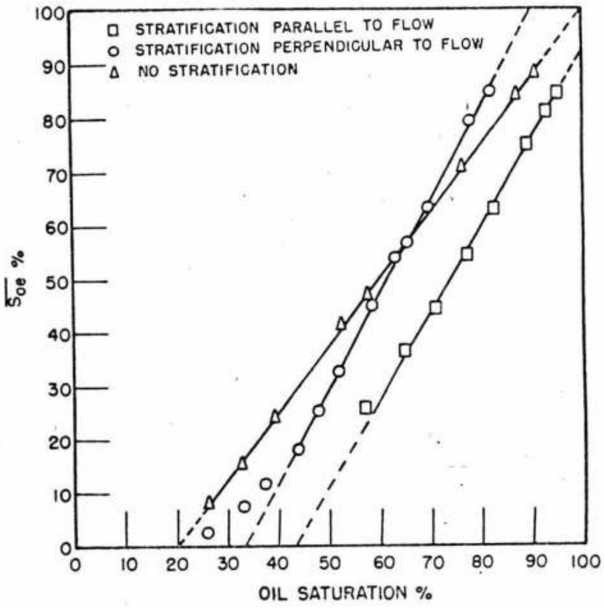

FIG. 5—$\overline{S_{oe}}$ VS OIL SATURATION SHOWING EFFECT OF STRATIFICATION.

distinct displacement pressures for the contrasting strata. The critical gas saturation is low and the gas relative permeability rises steeply as the oil saturation is reduced. This is undoubtedly a result of gas breaking through coarse strata while finer strata remain saturated. Also shown in Fig. 3 is the gas relative permeability curve on a similar core cut perpendicular to the bedding planes which indicates a very high critical gas saturation.

Fig. 4 shows the results of measurements made on a Berea sandstone which, when dry or fully saturated, appears to be homogeneous and isotropic. When the material is partially desaturated, however, thin and regularly spaced strata are apparent. Moreover, the air permeability of the dry cores is almost twice as great parallel to the bedding planes as perpendicular to them. Evidently the material is quite uniform, but it is not isotropic. The effect of the anisotropy is to increase greatly the critical gas saturation and to make the oil relative permeability curve steeper when flow is across the bedding planes.

In Ref. 1 an outline of a procedure for determining the end points, S_{or} and S_m, from gas relative permeability curves was given. The method involves making a plot of K_{rg} as a function of S_{oe}, according to Eq. 4. This is easily done by assuming values of S_{oe} and solving for K_{rg}. The resulting plot is used to obtain apparent values of effective saturation, $\overline{S_{oe}}$, from measured values of K_{rg}. $\overline{S_{oe}}$ is then plotted as a function of S_o, the oil saturation based on total pore volume. From the definition of S_{oe},

$$S_{oe} = \frac{S_o - S_{or}}{1 - S_{or}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

it follows that the plot of $\overline{S_{oe}}$ vs S_o will result in a straight line if Eq. 4 is valid. According to Eq. 4, S_{oe} should be unity when $S_o = 1$ and zero when $S_o = S_{or}$.

As explained in Ref. 1 the actual plot of $\overline{S_{oe}}$ vs S_o does not usually extrapolate to unity when $S_o = 1$, but instead to a value of S_o which is arbitrarily defined as S_m. The function S_{oe} vs S_o can usually be approximated by a straight line except in the region where K_{rg} approaches unity.

Many plots of $\overline{S_{oe}}$ vs S_o have been made to obtain S_{or} and thus the K_{ro} curve. A significant pattern of behavior has been observed, as is shown in Fig. 5. Cores having marked stratifications parallel to the direction of flow invariably extrapolate to values of $S_m > 1$, while those having stratifications perpendicular to the direction of flow give values of $S_m < 1$. Some cores give values of $S_m = 1$, indicating a precise agreement with Eq. 4, except in the region of low liquid saturations. Cores having values of $S_m = 1$ are uniform and nearly isotropic. A slight stratification parallel to flow may have little effect, but stratification perpendicular to flow, however slight, has a marked effect in decreasing S_m. It now seems probable that some stratification was the cause of the anomalous extrapolation of non-wetting phase resistivity index vs saturation, noted by Wyllie[2].

Unless S_m differs greatly from unity, the K_{ro} curve calculated from Eq. 3 will agree reasonably well with measured values of K_{ro}. This is another indication that oil relative permeabilities are less sensitive to slight stratification than are gas relative permeabilities. Cores which are cut parallel to the major strata of the reservoir often give values of $S_m < 1$. Apparently, slight differences in texture or cementation along the length of the cores are responsible.

The saturation, S_m, must not be confused with the critical gas saturation. Values of S_m greater than or equal to 1 do not indicate gas permeability at a liquid saturation of 1. Obviously, a gas saturation at least sufficient to fill a single continuous channel is necessary for gas permeability to exist. Nevertheless, gas relative permeability curves for isotropic cores, when extrapolated, often pass through a saturation of unity.

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