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Laboratory Measurement of Relative Permeabilities of Oil and Water in Sand

by

Khwaja Naweed SEDDIQI[*1], Zabihullah MAHDI[*2] and Shigeo HONMA[*3]

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Abstract

The relative permeability of two immiscible fluids in sand is measured in laboratory experiments based on the steady-state method. Water and kerosene, heavy oil, or lubricant oil are pumped simultaneously into a vertical sand column with different pumping ratios. Based on the change in fractional discharge measured at the outlet, a method for determining the relative permeability is developed focusing on the displacement mechanism in sand. The displacement of pore water by oil and the displacement of pore oil by water are examined. The relative permeability curves have different shapes depending on the kind of oil, and produce different amounts of residual oil. In designing waterflooding techniques to predict the oil recovery in petroleum reservoirs, it is necessary to assess the relative permeability of the reservoir oil in consideration of their characteristics.

Keywords: Petroleum reservoir engineering, Relative permeability, Two-Phase flow, Immiscible displacement in porous media, Steady-state method

1. Introduction

Relative permeability is an important conductive parameter controlling the immiscible displacement of multiphase fluid flow in a porous medium. Petroleum reservoirs with a simple single-phase fluid system are rare; reservoirs are usually saturated with at least two immiscible fluid phases such as gas and oil, oil and water, or gas, oil, and water[1)]. The relative permeability affects flow processes strongly when gas or water is injected into the reservoir. For example, in the waterflooding technique, water is injected into a reservoir to increase oil recovery.

The relative permeability is affected by many factors, including fluid saturation, saturation history, magnitude of the initial-phase saturation, wettability, rock pore structure, and temperature. The curves are plotted with wetting fluid saturation (usually water), S_w, ranging from the irreducible wetting-phase saturation, S_{wi}, to the residual oil saturation, S_{or}. Figure 1 shows the typical relative permeability curves reported by Aziz and Settari[2)]. As the wetting fluid saturation increases, the relative permeability of oil, k_{ro}, gradually decreases with oil desaturation, and the relative permeability of water gradually increases and reaches its maximum value, the end-point water permeability, k_{rws}.

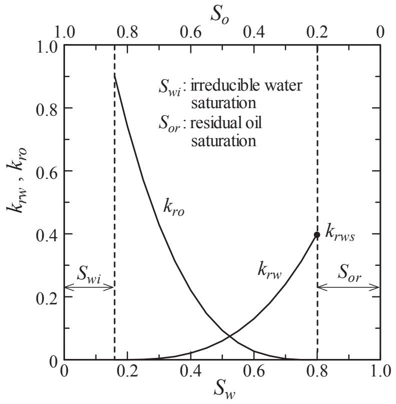


Fig. 1 Typical relative permeability curves of oil and water[2)].

The value is measured in laboratory experiments by the steady-state method or the unsteady-state method. The advantage of the steady-state method is that the calculation is simple and gives reliable values, although the experiments may be time-consuming. The unsteady-state method is rational and fast, but requires accurate consecutive measurements.[1)] In this paper, the relative permeabilities of water and kerosene, heavy oil, or lubricant oil, in sand are measured by the steady-state method. By changing the displacing fluid and the displaced fluid, the displacement mechanism of two immiscible fluids and the reliability of the calculation method are examined.

[*1] Graduate Student, Course of Civil Engineering
[*2] Research Student, School of Engineering
[*3] Professor, Department of Civil Engineering

2. Experimental Method

The experimental apparatus is shown in Fig. 2. Standard Toyoura sand with a particle diameter of D = 0.105–0.425 mm and a soil particle density of $\rho_s = 2.65$ g/cm^3 was packed into a column with a uniform density. The sand was initially saturated with deaerated water for the water displacement test, or saturated with oil for the oil displacement test.

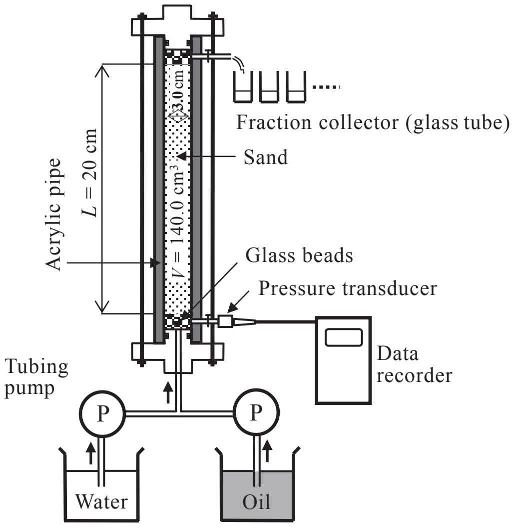


Fig. 2 Experimental apparatus.

Two tubing pumps were connected at the bottom of the column through which the displacing fluids (oil and water) were pumped at the same time with different pumping rates (e.g., q_w:q_o = 4:6). The pore liquids displaced by pumping were collected at the top of the column by fraction collectors (2 mL test tubes) until the fraction ratio of oil and water reached the pumping ratio (steady state). A pressure gauge was installed at the bottom of the column to measure pumping pressure.

3. Method for Determining Relative Permeability

Figure 3 shows a schematic diagram of the displacement of water by oil in a porous medium. Because soil pores contain immobile water, such as absorbed water and stagnant water, oil only displaces mobile water with velocity v_o, and mobile water velocity v_w, through the effective porosity, n_e, of the soil. The void ratio, e, and porosity n of the soil can be calculated by soil mechanics as[3)]

$$e = \frac{\rho_s}{\rho_d} - 1 \quad , \quad n = \frac{e}{1+e} \qquad (1)(2)$$

where ρ_s is the density of soil particles and ρ_d is the dry density of the packed soil. Letting void volume V_v be the unit pore volume, $1V_p$, oil and water flow through the effective pore volume, n_eV_v, and the fractional discharge of water is

$$f_{wd} = \frac{V_{wm}}{V_d} \qquad (3)$$

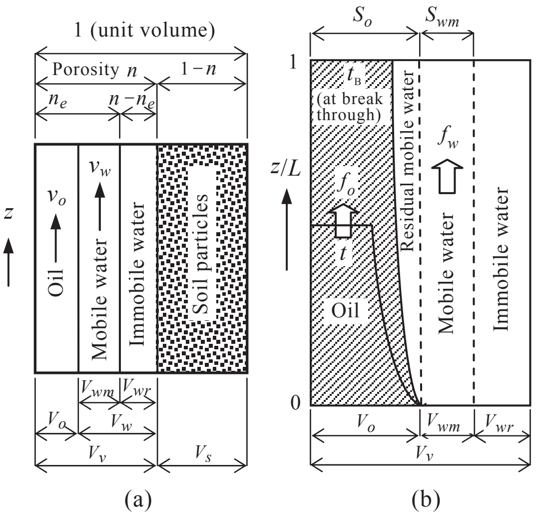


Fig. 3 Displacement mechanism of pore water by oil.

where V_{wm} is the volume of mobile water collected in the test tube and V_d is the volume of total liquid (water and oil) discharged at the outlet. When f_{wd} reaches the pumping ratio, $f_w = q_w/q_T$, a steady state is attained.

Figures 4 (a) and (b) show the change in f_{wd} and f_{od} with the change in V_p for the displacement of water by oil for $q_o = q_T$ and $q_w = 0$, and for $q_o = q_w = q_T/2$, where q_T is the total pumping rate. If the soil pores are initially saturated with water, the fractional discharge at the outlet, f_{wd}, is 1 until a particular pore volume is reached, and thereafter oil is discharged. Thus, f_{wd} begins to decrease and f_{od} increases. When water discharge ceases, only oil is discharged ($f_{od} = 1$). Therefore, the shaded area in Fig. 4 (a) shows the mobile pore water displaced by oil, and the degree of saturation is calculated as the shaded area/V_p. For pumping ratio $q_o = q_w = 0.5q_T$ (Fig. 4 (b)), when fractional discharges, f_{wd} and f_{od}, reach the fractional rate of pumping, f_w and f_o, the degree of saturation can be calculated in the same way. The shaded area in Fig. 4 (a) is always less than the total pore volume, V_v, and

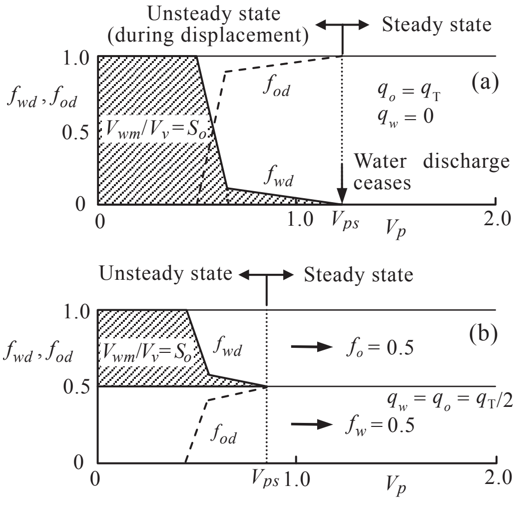


Fig. 4 Change in fractional discharge of pore water and oil.

the remaining volume is the immobile water volume (Fig. 3 (a)). The water saturation for this condition is expressed as

$$S_w = 1 - \int_0^{V_{ps}} (f_{wd} - f_w)\, dV_p \qquad (4)$$

If the pumping rate is $q_o = q_T$ and $q_w = 0$, the water saturation calculated by Eq. (4) represents the irreducible water saturation, S_{wi}. By changing the rate of pumping for oil and water in stages, we can obtain the degree of saturation of both phases at each rate.

The relative permeability of oil and water, k_{ro} and k_{rw}, are calculated as follows. Darcy's law for oil and water flow through a porous medium can be written as

$$q_o = \frac{k k_{ro} A}{\mu_o} \frac{dp_o}{dz} \quad , \quad q_w = \frac{k k_{rw} A}{\mu_w} \frac{dp_w}{dz} \qquad (5)(6)$$

where k is the intrinsic permeability of the medium ($k = 1.88 \times 10^{-7}$ cm^2 for Toyoura sand), A is the cross-sectional area for permeation ($A = 7.07$ cm^2), and μ_o and μ_w are the dynamic viscosity of oil and water, respectively (Table 1).
From Eqs. (5) and (6), k_{ro} and k_{rw} are calculated by

$$k_{ro} = \frac{q_o \mu_o}{kA} / \frac{p}{L} \quad , \quad k_{rw} = \frac{q_w \mu_w}{kA} / \frac{p}{L} \qquad (7)(8)$$

Here, the pressure gradients, p/L, are the same magnitude because the fluid pressure measured at the inlet is the same for oil and water. The physical properties of the oils and water are listed in Table 1.

Table1 Physical properties of oils[4].

Properties	Kerosene	Heavy oil	Lubricant oil
Density ρ (g/cm^3)	0.795	0.837	0.880
Dynamic viscosity μ (Pa·s)	0.00242	0.0167	0.0250

Notes: ρ_w = 1.00 g/cm^3, μ_w = 0.001 Pa·s

If soil is initially saturated with oil and displaced by water, the relative permeability and degree of saturation may be assessed in the same manner.

4. Results and Discussion

Table 2 and Fig. 5 show the relative permeabilities obtained from water displacement by oil. The relative permeability of water, k_{rw}, decreased as the water saturation decreased, and the relative permeability of oil, k_{ro}, increased with the desaturation of pore water. A considerable amount of oil was stored in sand pores, expressed as the residual oil saturation, S_{or}, which was large for kerosene and lubricant oil. The amount of irreducible water saturation, S_{wi}, decreased as the

Table 2 Relative permeabilities for water displacement by oils.

Kerosene			Heavy oil			Lubricant oil		
S_w	k_{rw}	k_{ro}	S_w	k_{rw}	k_{ro}	S_w	K_{rw}	K_{ro}
0.17	0.00	0.91	0.11	0.00	0.97	0.08	0.00	0.43
0.25	0.02	0.64	0.17	0.00	0.68	0.09	0.00	0.42
0.32	0.05	0.41	0.22	0.01	0.46	0.13	0.00	0.37
0.37	0.07	0.32	0.23	0.02	0.46	0.19	0.00	0.31
0.40	0.09	0.22	0.27	0.02	0.41	0.26	0.00	0.23
0.42	0.11	0.20	0.39	0.02	0.23	0.33	0.01	0.22
0.47	0.13	0.12	0.45	0.03	0.16	0.41	0.01	0.21
0.54	0.15	0.06	0.53	0.03	0.10	0.47	0.02	0.17
0.63	0.22	0.01	0.62	0.04	0.05	0.53	0.02	0.14
—	—	—	0.76	0.07	0.00	0.55	0.04	0.12

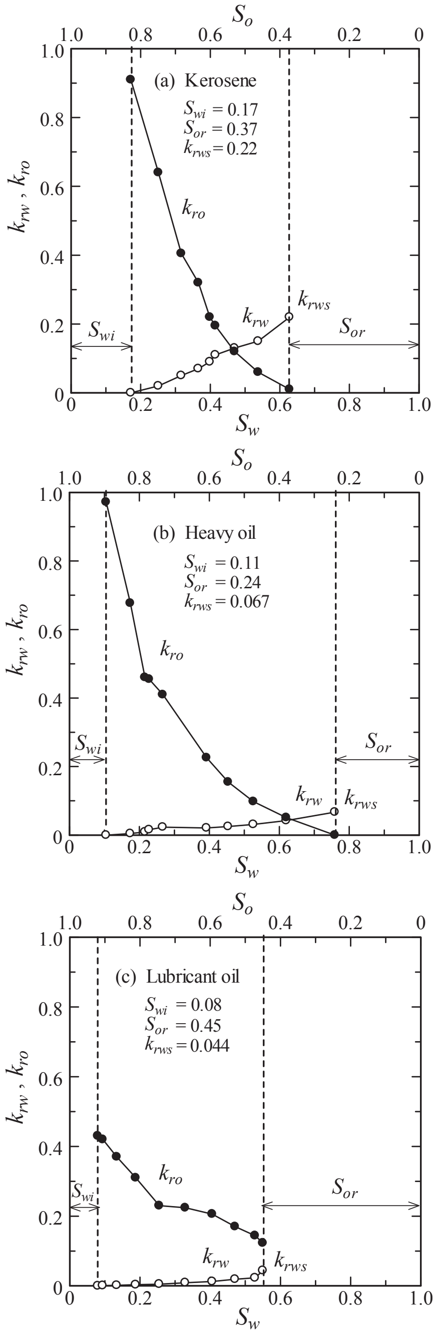
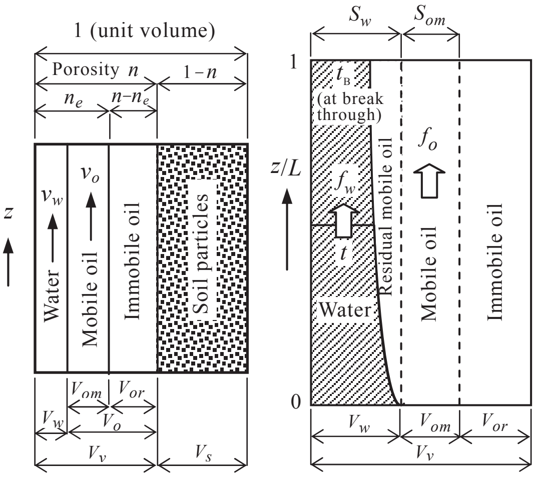


Fig. 5 Relative permeability curves for water displacement by oils.

oil viscosity increased (Table 1).

In the lubricant oil displacement test (Fig. 5 (c)), k_{rw} was smaller than for other oils, and k_{ro} did not reach zero at the maximum water saturation (S_{or}). This implies a steady state was not achieved and the pore water was still displaced by the oil, even though the measurement was performed for more than 3 h in each stage.

Next, we discuss the relative permeability data obtained from the oil displacement by water. These data are necessary for designing waterflooding techniques to predict the amount of oil recovery by injecting water into reservoirs.[5] The displacement mechanism for this condition is shown in Figs. 6 and 7.



(a) (b)

Fig. 6 Displacement mechanism of pore oil by water.

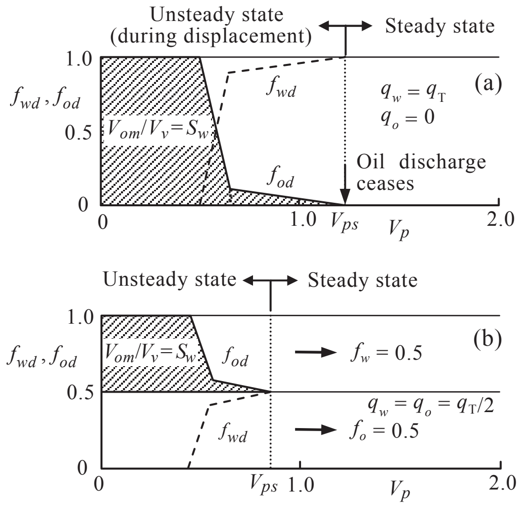


Fig. 7 Change in fractional discharge of pore oil and water.

The degree of water saturation for this case is calculated by

$$S_w=\int_0^{V_{ps}}(f_{od}-f_o)\,dV_p = 1-S_o \qquad (9)$$

Table 3 and Fig.8 show the relative permeabilities obtained from the tests. The relative permeablity curves followed a

Table 3 Relative permeabilities for oil displacement by water.

Kerosene			Heavy oil			Lubricant oil		
S_w	k_{rw}	k_{ro}	S_w	k_{rw}	k_{ro}	S_w	k_{rw}	k_{ro}
0.17	0.00	1.00	0.12	0.00	0.95	0.15	0.00	0.39
0.34	0.03	0.55	0.15	0.01	0.77	0.17	0.00	0.37
0.36	0.04	0.42	0.18	0.01	0.64	0.18	0.00	0.31
0.41	0.08	0.35	0.24	0.02	0.54	0.21	0.00	0.29
0.44	0.10	0.25	0.28	0.03	0.45	0.24	0.00	0.28
0.47	0.11	0.20	0.34	0.03	0.36	0.29	0.00	0.24
0.50	0.15	0.18	0.44	0.04	0.27	0.34	0.00	0.23
0.52	0.19	0.11	0.50	0.04	0.19	0.40	0.00	0.21
0.55	0.21	0.07	0.60	0.05	0.10	0.52	0.01	0.11
0.63	0.34	0.00	0.73	0.06	0.00	—	—	—

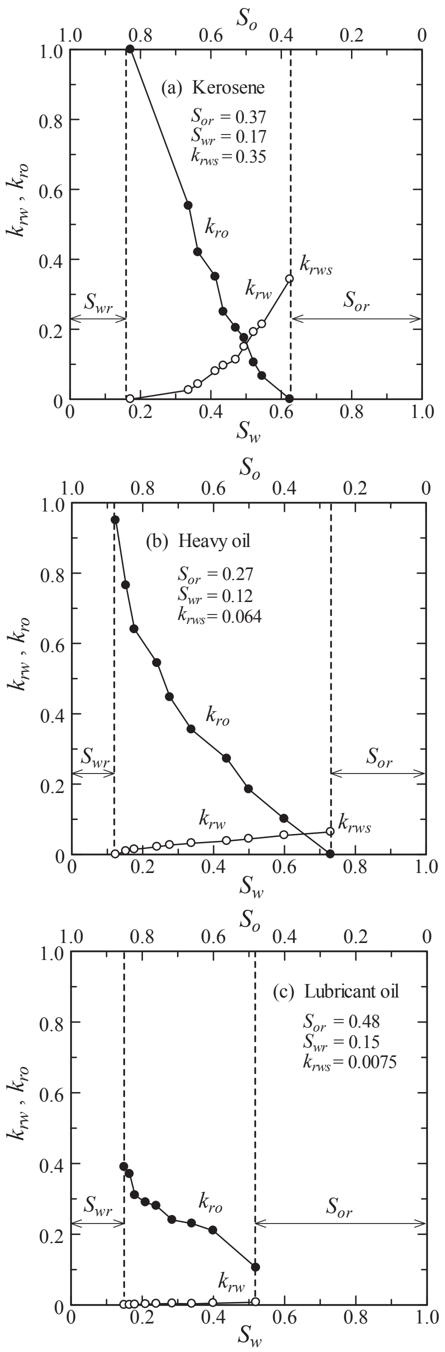


Fig. 8 Relative permeability curves for oil displacement by water.

similar trend with the change in saturation (compare Figs. 5 and 8) regardless of the displacement order. However, for lubricant oil, which has a large viscosity, the range of effective saturation where oil is mobile in sand was narrow in the oil displacement compared with the water displacement. The relative permeability of water, k_{rw}, was small for this oil in both displacement processes, which does not mean that water was immobile in the soil pores. In Eqs. (5) and (6), the amount of flow of oil and water through sand is affected by the relative permeabilities and by the viscosity of the fluid. The viscosity of water is smaller than that of lubricant oil, q_w does arise during the displacement.

Our results show that typical relative permeability curves with different residual oil and water saturations can be used for designing waterflooding techniques to predict the amount of oil recovery by injecting water into oil reservoirs. The rate of advance of the waterfront can be calculated based on the Buckley-Leverett frontal displacement theory by using fractional flow curves evaluated from the relative permeability curves[6).

5. Conclusion

The immiscible displacement of oil and water was used to measure the relative permeabilities of the fluids with the steady-state method. The major conclusions obtained from this study are as follows.

1) The relative permeability of a two-phase fluid system can be obtained with good accuracy by the steady-state method, even though the experiments are time-consuming. The degree of saturation of the medium by displacing fluid can be evaluated as the fractional discharge of displaced fluid when it was equal to the pumping ratio of displacing fluids.

2) Relative permeability curves for displacing water with oils and vice versa, were similar regardless of the displacement order. The amount of residual oil and water in soil pores are different depending on the oil properties.

3) The advance of the waterfront in petroleum reservoirs can be calculated based on the Buckley-Leverett frontal displacement theory by using typical fractional flow curves evaluated from the relative permeability curves. Our laboratory measurements with the steady-state method provided reasonably accurate values for this evaluation.

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