Laboratory Measurement of Relative Permeability of Immiscible Fluids in Sand

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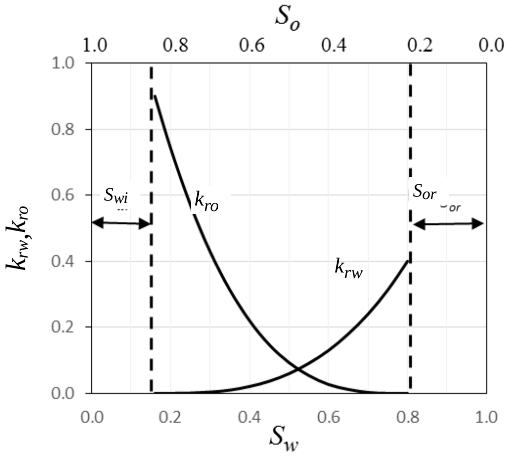
1. Introduction

Relative permeability is the important parameter controlling the immiscible displacement of multiphase fluids flow in porous medium. Fig. 1 shows a typical relative permeability curve of oil and water in sandstone reported by Aziz and Settari[1)]. As the wetting fluid desaturation, S_w, (usually water) increases, the relative permeability of oil, k_{ro}, gradually decreases with the saturation of oil, and inversely the relative permeability of water gradually increases. Irreducible water saturation, S_{wi}, and residual oil saturation, S_{or}, are also important parameter controlling displacement.



Relative permeabilities of oils (Kerosene and Heavy oil) and water in sand were measured in the laboratory by Steady-State (SS) method. As a result of the experiment, irreducible water saturation, S_{wi}, residual oil saturation, S_{or}, and relative permeability curves for Kerosene and Heavy oil were determined successfully.

2. Outline of the Experiment

Experimental apparatus depicted in Fig. 2 was used in the experiment. Standard sand (Toyoura sand) of the particle diameter $D = 0.105 \sim 0.425$mm was packed in the column with a constant density and it was initially saturated by water (displaced fluid). Double tubing pumps were connected at the bottom of the column from which displacing fluids (oil) were pumped into the saturated sand with different pumping rates (e.g. $q_w : q_o = 6 : 4$). The pore liquid displaced by pumping was collected at the top of the column with fraction collectors (2cc test tube) until fraction ratio of oil and water reaches to the pumping ratio (steady state). The pressure gauge was installed at the bottom of the column to measure pumping pressure.

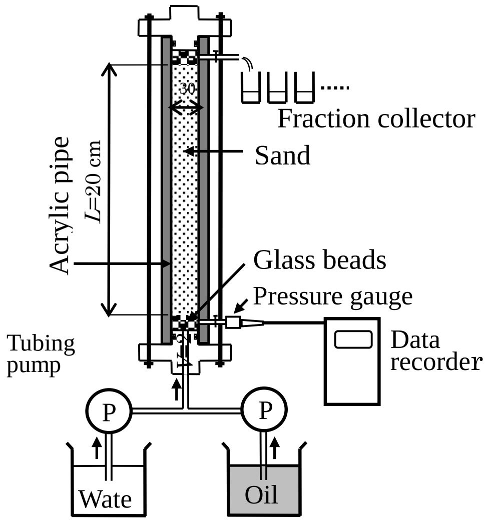


Fig. 2 Experimental apparatus.

3. Method for Determining Relative Permeability

Fig. 2 shows a schematic diagram of displacement of pore water by oil. Because there exists immobile water (absorbed water) in soil pore, oil displaces only mobile water with velocity v_o together with mobile water velocity v_w through the effective porosity (n_e).

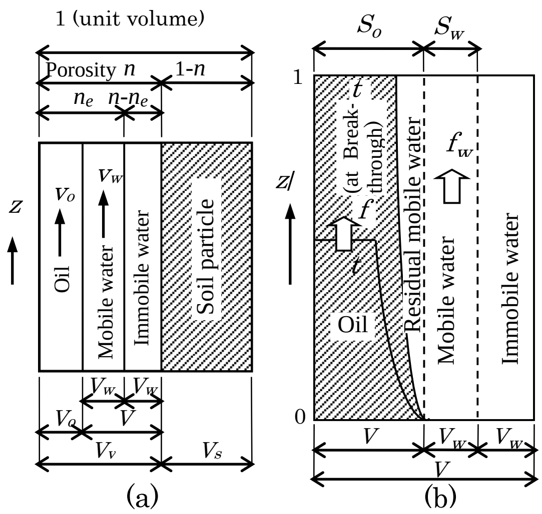


Fig. 3 Displacement mechanism.

The void ratio e and porosity n of soil can be calculated by soil mechanics as

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

where ρ_d is dry density of soil and ρ_s is the density of soil particle. Letting void volume V_v as the unit pore volume $1V_p$, oil and water flow through effective pore volume $ne\ V_v$, and letting fractional discharge of water as

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$$f_{wd} = \frac{v_{wm}}{v_d} \qquad (3)$$

(v_{wm} is the volume of water collected by test tube and v_d is the volume of liquid (2.0cc)) at discharge site.

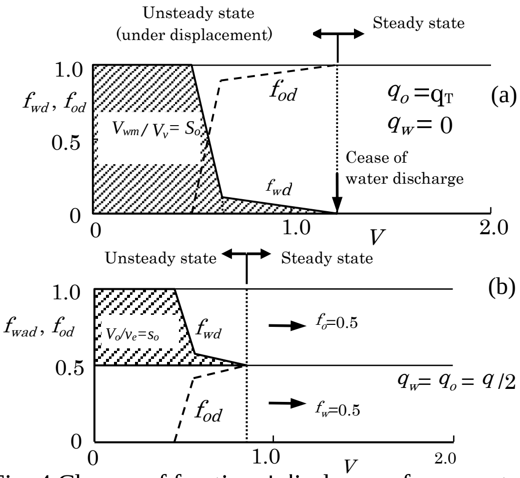

Fig. 4 Change of fractional discharge of pore water and oil.

Fig. 4 illustrates the change of f_{wd} and f_{od} with the change of pore volume v_p; (a) displacement of pore water by oil only, $q_o = q_T$ and $q_w = 0$, (b) $q_w = q_o = {}^{q_T}/_{2}$ (q_T is the total pumping rate). Since soil pore was initially saturated by water, the fractional discharge at outlet f_{wd} is 1 until some pore volume. After that some amount of oil is discharged so that f_{wd} decrease and f_{od} increase. When water discharge is ceased, only the oil is discharged ($f_{od} = 1$). Therefore, the slashed area of Fig. 4 (a) indicates mobile pore water displaced by oil and the degree of saturation of oil, S_o, can be computed the slashed area/ v_p. Fig. 4 (b) illustrates the case of the pumping ratio of $q_w = q_o = 0.5$. When fractional discharge, f_{od} and f_{wd}, reach to the fractional rate of pumping, f_o and f_w, the oil saturation in pore can be computed by the same way. The slashed area of Fig.4 (a) is less than the total pore volume, v_v, and the remaining volume this is means the immobile waters

$$S_{wi} = 1 - \int_0^{v_p} f_{wd}\, dv_p \qquad (4)$$

(irreducible water saturation, S_{wi}) shows in Fig. 3. This is mathematically expressed as;

By changing the pumping rate of oil and water, we can evaluate the average degree of saturation, S_o, and S_w, at steady state. The relative permeability of oil and water, k_{ro} and k_{rw}, are computed from Darcy's law as

$$q_o = \frac{k\, k_{ro} A}{\mu_o} \frac{\partial p_o}{\partial z} \quad , \quad q_w = \frac{k\, k_{rw} A}{\mu_w} \frac{\partial p_w}{\partial z} \qquad (5)\ (6)$$

where k is the intrinsic permeability of the medium ($k = 1.0 \times 10^{-7}$ cm^2), A is the cross-sectional area of sand column, μ_o and μ_w are the dynamic viscosities of oil and water respectively. From Eqs. (5) and (6), k_{ro} and k_{rw} can be 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 are the same because the fluid pressure of mixed fluid, P is measured at the inlet of soil column (P is the pressure measured by pressure gauge as show in Fig. 1). The physical properties of oil and water are listed in Table 1.

Table 1 Physical properties of oils and water.

Properties	Kerosene	Heavy oil	Water
Density $\rho({}^{g}/_{cm^3})$	0.795	0.837	1.00
Dynamic Viscosity $\mu(Pa \times s)$	0.00242	0.0167	0.001

If soil is initially saturated by oil and displaced by water, relative permeabilities and irreducible oil saturation and residual water saturation are obtained by the same way.

4. Results and Discussion

Table 2 shows relative permeabilities obtained from the steady-state experiments.

Table. 2 Relative permeability for displacing water

Heavy oil			Kerosene		
S_w	k_{rw}	k_{roh}	S_w	k_{rw}	k_{rok}
0.10	0.00	1.00	0.16	0.00	1.00
0.18	0.00	0.68	0.25	0.00	0.64
0.24	0.00	0.49	0.32	0.01	0.43
0.33	0.02	0.28	0.37	0.01	0.32
0.41	0.04	0.15	0.52	0.06	0.09
0.51	0.10	0.05	0.61	0.13	0.03
0.63	0.21	0.01	0.66	0.17	0.01
0.69	0.29	0.00	0.71	0.23	0.00
0.79	0.46	0.00	0.82	0.40	0.00

$S_{wi} = 0.10$, $S_{or} = 0.24$ $\quad$ $S_{wi} = 0.16$, $S_{or} = 0.18$

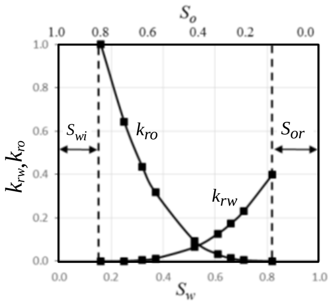

Fig. 5 Relative permeability curves for displacing water by kerosene.

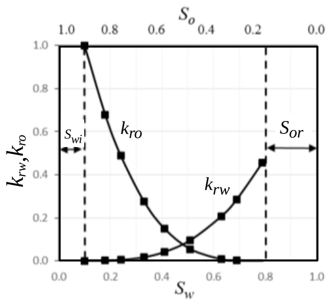

Fig. 6 Relative permeability curves for displacing water by heavy oil.

Fig. 5 and Fig. 6 illustrate the relative permeability curves drawn using the data of Table 2. It is seen from the figures, relative permeability of water, k_{rw}, gradually decreases with desaturation of water and inversely, relative permeability of oil, k_{ro}, rapidly increases.

The residual oil saturations, s_{or}, are the same for two oils, but irreducible water saturations, s_{wi}, of heavy oil is smaller than that of kerosene.

References:

1) K. Aziz and A. Settari : Petroleum Reservoir Simulation, (Applied Science Publishers, 1979)
2) A.Y. Dandekar: Petroleum Reservoir, Rock and Fluid Properties, (CRC Press, 2013), pp.45-83.
3) R.C. Craft and M. Hawkins, Revised by R.E. Terry: Applied Petroleum Reservoir Engineering, (Prentice-Hall, 1991), pp.1-6, 335-390.