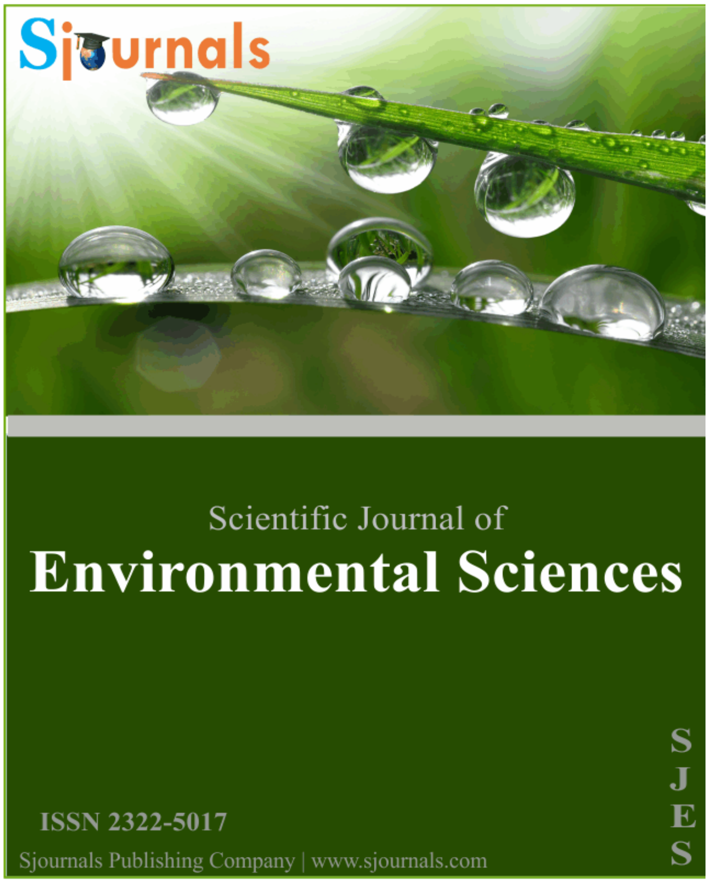
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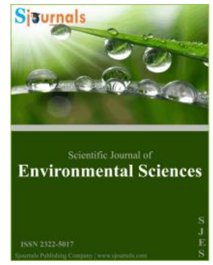

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Original article

Laboratory measurement of relative permeabilities of oil and water in sand

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A B S T R A C T

The relative permeability of two immiscible fluids in sand is measured in the laboratory based on the steady-state method. Three sorts of oils, Kerosene, heavy oil and lubricant oil, and water are pumped simultaneously into a vertical sand column with different pumping ratio. From 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. Two sorts of experiments, one is the displacement of pore water by oil, the other is the displacement of pore oil by water, are carried out. It is revealed that the relative permeability curves display tolerably different shape owing to the kinds of oils, and produce different amount of residual oils. For the design of the waterflooding technique to predict the oil recovery in petroleum reservoir, it is necessary to asses the relative permeability of the reservoir oil taking care of their characteristics.

1. Introduction

Relative permeability is an important conductive parameter controlling immiscible displacement of multiphase fluids flow in a porous medium. Petroleum reservoirs having simple single-phase fluid system seldom exist because reservoirs are saturated with at least two immiscible fluid phases such as gas and oil or oil and water or gas, oil and water (Dandekar, 2013). The relative permeability significantly affects flow processes when gas or water is injected into the reservoir. For example, the technique of injecting water into a reservoir is widely used in petroleum engineering to increase oil recovery that is known as the waterflooding technique. The relative permeability is affected by many factors including fluid saturations, saturation history, magnitude of initial-phase saturation, wettability, effect of rock pore structure and temperature so on. 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 illustrates 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 desaturation of oil, and inversely the relative permeability of water gradually increases and reaches to its maximum value k_{rws} (end-point water permeability). The value is measured through laboratory experiments by steady-state (SS) method or unsteady-state (USS) method. The advantage of steady-state method is that the calculation is relatively simple and gives reliable values, even though the entire testing process may be time-consuming. Unsteady-state method is rational and speedy, but requires accurate consecutive measurement (Dandekar, 2013).In this paper, the relative permeabilities of water and three different oils, Kerosene, heavy oil and lubricant oil, in sand are measured through SS method. By changing the displacing fluid and the displaced fluid, the displacing mechanism of two immiscible fluids and the propriety of the calculation method are discussed.

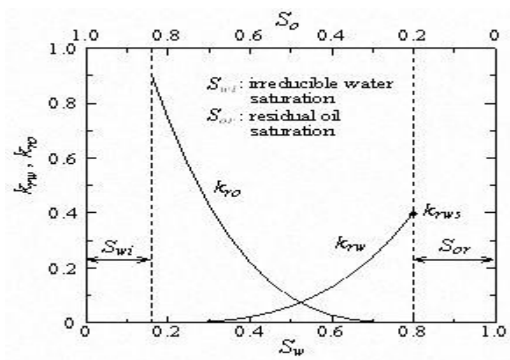

Fig. 1. Typical relative permeability curves of oil and water (Aziz and Settari, 1979).

2. Materials and methods

Experimental apparatus depicted in Figure 2 was used in the experiment. Standard sand (Toyoura sand) of the particle diameter of $D = 0.105\text{-}0.425$mm and the density of soil particle $\rho_s=2.65g/cm^3$ was packed in the column with a constant density. It was initially saturated by deaired water for the water displacement test, or saturated by oil first for oil displacement test. Two tubing pumps were connected at the bottom of the column by which displacing fluids (oil and water) are 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 (2cc test tube) until fraction ratio of oil and water reaches to the pumping ratio (steady state). Pressure gauge was installed at the bottom of the column to measure pumping pressure.

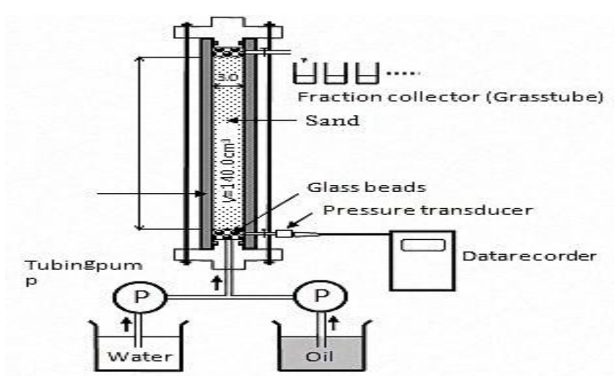

Fig. 2. Experimental apparatus.

3. Method for determining relative permeability

Figure 3 shows a schematic diagram of the displacement of water by oil in a porous medium. Because there exists immobile water, i.e., absorbed water and stagnant water in soil pores, oil displaces only mobile water with velocity v_o, together with the mobile water velocity v_w, through effective porosity n_e of the soil. The void ratio e and porosity n of the soil may be calculated by soil mechanics as (Cernica, 1995);

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

Where ρ_s is the density of soil particle, ρ_d is the dry density of soil packed. Letting void volume V_v as the unit pore volume, 1 V_p, oil and water will be flowing through effective pore volume, n_eV_v, and letting fractional discharge of water as;

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

Where V_{wm} is the volume of mobile water collected by the test tube and V_d is the volume of total liquid (water and oil) discharged at the outlet. When f_{wd} reaches to the pumping ratio $f_w = q_w / q_T$, a steady state is said to be attained. Figure 4 illustrates the change in f_{wd} and f_{od} with the change in Vp; (a) shows the displacement of water by oil only, $q_o = q_T$ and $q_w = 0$, (b) is the case of $q_o = q_w = q_T/2$ (q_T is the total pumping rate). If soil pore was initially saturated by water, the fractional discharge at the outlet f_{wd} is 1 until some pore volume, thereafter some amount of oil would be discharged. Thus, f_{wd} begins to decrease and f_{od} increases. When water discharge is ceased, only oil is discharged (f_{od} = 1). Therefore, the slashed area in Fig. 4 (a) indicates the mobile pore water displaced by oil, and the degree of saturation for the case is computed as the slashed area / Vp. Figure 4 (b) illustrates the case of pumping ratio $q_o = q_w = 0.5q_T$. When fractional discharges, f_{wd} and f_{od}, reach to the fractional rate of pumping, f_w and f_o, the degree of saturation can be calculated in the same way. The slashed area in Fig.4 (a) is always less than the total pore volume, V_v, and the remaining is the immobile water volume previously shown in Fig.3 (a). The water saturation for this situation is mathematically expressed as;

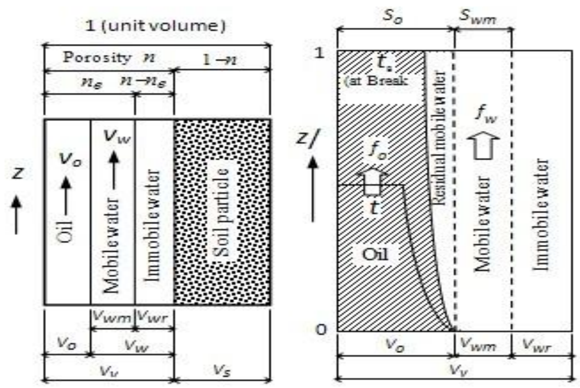

Fig. 3. Displacement mechanism of pore water by oil.

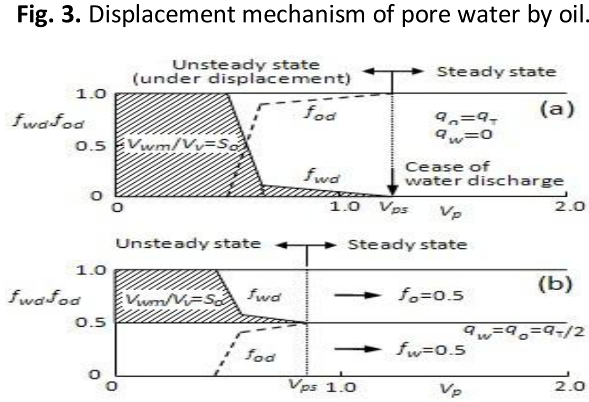

Fig. 4. Chang in fractional discharge of pore water and oil.

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

If 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}, arecalculated as follows. Darcy's law for oil and water flow through porous medium can be written as;

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

Where k is the intrinsic permeability of the medium ($k = 1.88\times10^{-7}\text{cm}^2$ for Toyourasand), A is the cross-sectional area for permeation ($A = 7.07\text{cm}^2$), $\mu_o$and μ_w are the dynamic viscosity of oil and water, respectively (Table1). From Eqs. (5) and (6), k_{ro} and k_{rw} are calculated by;

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

Here, pressure gradients are the same magnitude p/L, because fluid pressure measured at the inlet is the same for oil and water. The physical properties of oils and water are listed in Table 1. If soil is initially saturated by oil and displaced by water, the relative permeability and degree of saturation may be assessed in the same manner.

Table 1
Physical properties of oils (Tamai and Honma, 2012).

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=1.00g/cm^3, μ_w=0.001Pa・ s

4. Results and discussion

Table 2 and Fig. 5 show the relative permeabilities obtained from the experiments for water displacement by oils. It is seen from the figures that the relative permeability of water, k_{rw}, decreases as saturation of water decreases, and the relative permeability of oil, k_{ro}, increases as the saturation of pore water. A considerable amount of oil is stored in sand pores, denoting the residual oil saturation, S_{or}, that is remarkable for Kerosene and lubricant oil. It is also noticed that the amount of irreducible water saturation, S_{wi}, decreases as the viscosity of oil increases (see Table 1). In the result by lubricant oil displacement test (Fig.5(c)), k_{rw} shows very small value compared to other oils, and k_{ro} does not reach to zero at the maximum water saturation (S_{or}). This implies steady state may not be achieved and the pore water was still under displacement by the oil, even though the measurement was continued more than three hours in each stage.

Subsequently, relative permeability data obtained from the experiments for oil displacements by water are presented. These data are necessary for the design of waterflooding technique to predict the amount of oil recovery by artificially injecting water into the reservoir (Craft and Hawkins, 1991). The displacement mechanism for this situation is illustrated in Fig. 6 and Fig. 7.

Table 3 and Fig. 8 show the relative permeabilities obtained from the tests. It is very interesting the relative permeability curves follow the almost same rout with change in saturation (compare Fig. 5 and Fig. 8) regardless of the displacement order. However, in lubricant oil of which viscosity is very large, the effective saturation where oil is mobile in sand becomes narrow in the oil displacement compared to the water displacement. The relative permeability of water, k_{rw}, is very small for this oil in both displacement processes, which does not mean water is immobile in soil pores. If we return to Eqs. (5) and (6), the amount of flow of oil and water through sand is affected not only by relative permeabilities but also by the viscosity of the fluid. The viscosity of water is very small than that of lubricant oil, q_w does arise during the displacement.

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

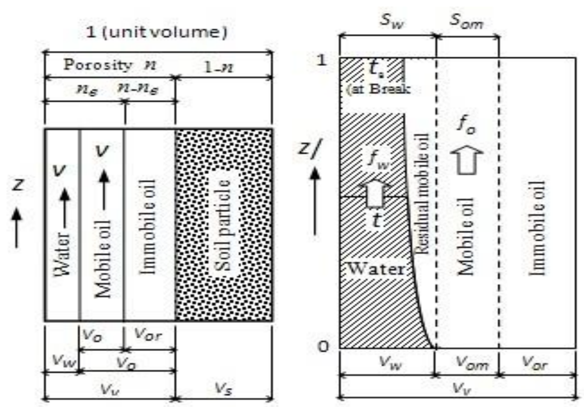

Fig. 6. Displacement mechanism of pore oil by water.

The degree of water saturation for this case is calculated by;

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

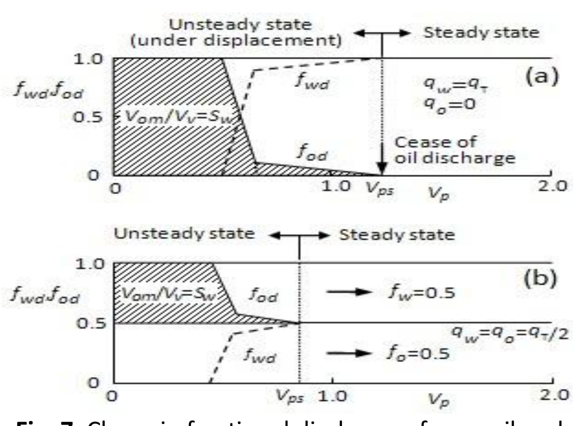

Fig. 7. Chang in fractional discharge of pore oil and water.

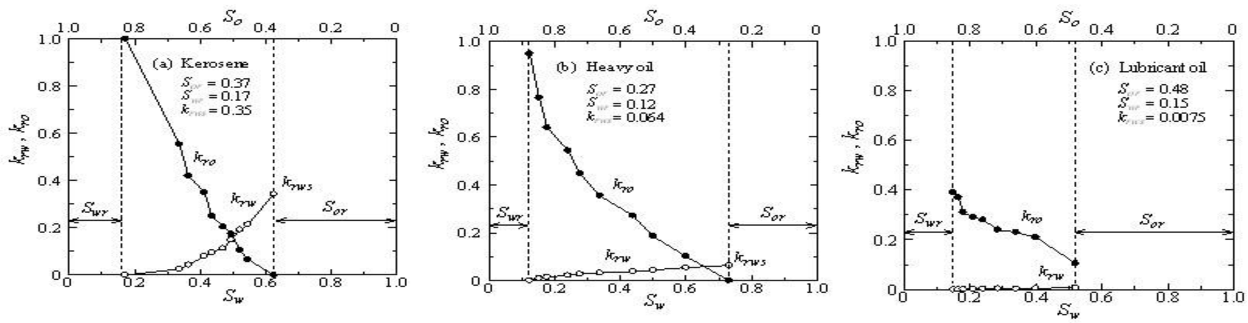

Fig. 8. Relative permeability curves for oil displacement by water.

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	0.00000	0.31
0.41	0.08	0.35	0.24	0.02	0.54	0.21	0.0000	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	0.011	0.11
0.63	0.34	0.00	0.73	0.06	0.00	—	—	—

From all of the results reported herein, typical relative permeability curves with different residual oil and water saturations should be used for the design of waterflooding technique to evaluate the amount of oil recovery by artificially injecting water into the reservoir. The rate of advance of water front can be calculated based on the Buckley-Leverett frontal displacement theory using fractional flow curves that are evaluated from the relative permeability curves (Nazari et al., 2015).

5. Conclusion

By laboratory experiments for immiscible displacements of oil and water, the relative permeabilities for each fluids were measured successfully based on the steady-state method. The major conclusions obtained through this study are as follows:

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

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

3) The advance of water front in petroleum reservoir can be calculated based on the Buckley-Leverett frontal displacement theory by using typical fractional flow curves evaluated from the relative permeability curves. The laboratory measurement by the steady-state method provides fairly accurate values for the evaluation.

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