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Effect of Fractional Flow Curves on the Heavy Oil and Light Oil Recoveries in Petroleum Reservoirs

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***Abstract*—**This paper evaluates and compares the effect of fractional flow curves on the heavy oil and light oil recoveries in a petroleum reservoir. Fingering of flowing water is one of the serious problems of the oil displacement by water and another problem is the estimation of the amount of recover oil from a petroleum reservoir. To address these problems, the fractional flow of heavy oil and light oil are investigated. The fractional flow approach treats the multi-phases flow rate as a total mixed fluid and then describes the individual phases as fractional of the total flow. Laboratory experiments are implemented for two different types of oils, heavy oil, and light oil, to experimentally obtain relative permeability and fractional flow curves. Application of the light oil fractional curve, which exhibits a regular S-shape, to the water flooding method showed that a large amount of mobile oil in the reservoir is displaced by water injection. In contrast, the fractional flow curve of heavy oil does not display an S-shape because of its high viscosity. Although the advance of the injected waterfront is faster than in light oil reservoirs, a significant amount of mobile oil remains behind the waterfront.

***Keywords*—**Fractional flow curve, oil recovery, relative permeability, water fingering.

I. Introduction

THE relative permeability data basically signify the relative conductive capacity of the flow of a reservoir rocks when it is saturated with more than one fluid phase. Laboratory measurement technique for obtaining the two-phase relative permeability data based on the flow experiments are fairly well established. The steady state method is used to analyze the fractional flow of water and relative permeability of heavy oil and light oil. The steady-state method aims to achieve the steady-state flow at different fractional flow ratios yielding unique core saturation at each ratio [1]. The results are easy to interpret; however, it takes a long time to achieve steady-state conditions. During the steady state experiments, the fractional flow, relative permeability and breakthrough time of the injected fluid are recorded. The two-phase relative permeability, as a function of different saturation of water of the samples, can then be measured based on the fractional flow theory [2]. Furthermore, relative permeabilities of oil and water mostly depend on the saturation of water. Therefore, the experiments are performed with different ratios of water saturation.

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II. Laboratory Experiments

The procedure for determining of oil-water relative permeabilities from the steady state experiments requires very comprehensive steps of various water saturation; the procedure is illustrated in Fig. 1.

1. The process starts with complete water saturation of the core sample, followed by the oil flood down to irreducible water saturation, and the determination of the effective permeability of oil at irreducible water saturation.

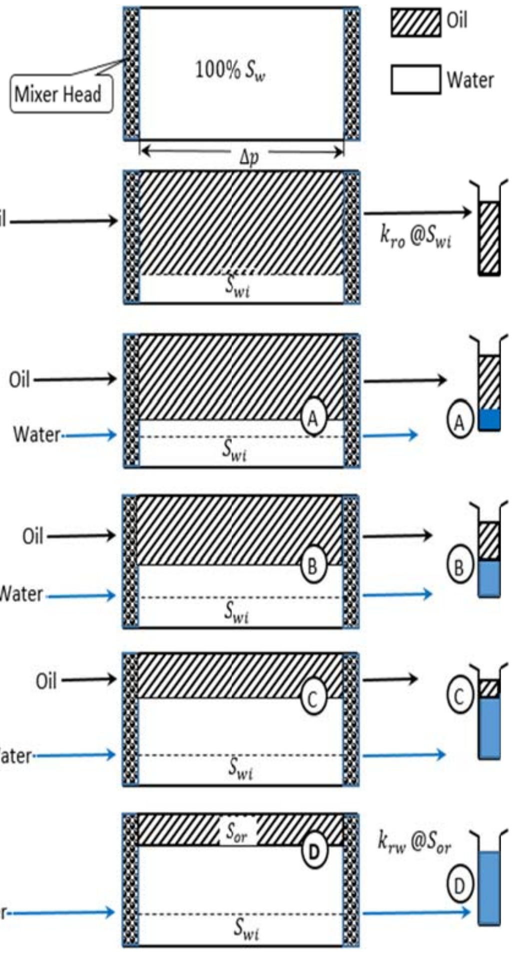

Fig. 1 Oil and water flow under various saturation [2], [3]

2. In the subsequent steps, the objective is to increase the water-phase saturation steadily so that a number of data points, on the relative permeability curve can be obtained. The two immiscible fluids, oil, and water, are injected

simultaneously into the core sample through a mixer head at a certain volumetric flow rate ratio, and the volume of fluids produced and pressure drop are recorded. The simultaneous injection of oil and water is continued until the injection ratio is equal to the production ratio when the system is considered to be in the steady state and the existing saturations are stable the effective permeabilities at specific saturations are calculated which is shown in the next section.

3. The volumetric flow rate ratio is then gradually increased so that the oil phase is replaced by the water phase so that the water phase saturation increases. The process is terminated when steady state is reached and is then followed by an even higher water to oil ratio of injection.
4. In the final step, only water is injected down to residual oil saturation. Based on the flow rate of water injection and the observed steady pressure drop, the effective permeability to water at residual oil saturation is calculated. This point constitutes the other end point of the oil-water relative permeability curve [2].

III. Relative Permeability

It is expected that permeability of two phases is lower than single phase. Since one of these phases occupies the part of the pore space and may also be affected by interaction with other phases. Therefore, the behavior of these phases is interpreted by relative permeabilities. The relative permeability of oil is defined as:

The equation started by Darcy's law.

$$q_o = -\frac{kk_{ro}A}{\mu_o}\left(\frac{\partial p_o}{\partial x} + \rho_o g sin\alpha\right) \tag{1}$$

$$q_w = -\frac{kk_{rw}A}{\mu_w}\left(\frac{\partial p_w}{\partial x} + \rho_w g sin\alpha\right) \tag{2}$$

and replace the water pressure by $p_w = p_o - p_{cow}$, so that

$$q_w = \frac{kk_{rw}A}{\mu_w}\left(\frac{\partial(p_o - p_{cow})}{\partial x} + \rho_w g sin\alpha\right) \tag{3}$$

Here, p_{cow} is the capillary pressure between oil and water. After rearranging, the equations may be written as:

$$-q_o \frac{\mu_o}{kk_{ro}A} = \frac{\partial p_o}{\partial x} + \rho_o g sin\alpha \tag{4}$$

$$-q_w \frac{\mu_w}{kk_{rw}A} = \frac{\partial p_o}{\partial x} - \frac{\partial p_{cow}}{\partial x}\rho_w g sin\alpha \tag{5}$$

Subtracting (4) from (5), we can get

$$-\frac{1}{kA}\left(q_w \frac{\mu_w}{k_{rw}} - q_o \frac{\mu_o}{k_{ro}}\right) = -\frac{\partial p_{cow}}{\partial x} + \Delta\rho\ g sin\alpha \tag{6}$$

Substituting

$$q_T = q_w + q_o\,, \qquad f_w = \frac{q_w}{q_o} \tag{7}$$

and solving for the fractional flow of water, we obtain the following expression for the fraction of flowing water:

$$f_w = \frac{1 + \frac{kk_{ro}A}{q_T \mu_o}\left(\frac{p_{cow}}{\partial x} + \Delta\rho\ g sin\alpha\right)}{1 + \frac{k_{ro}\mu_w}{k_{rw}\mu_o}} \tag{8}$$

For horizontal flow and removing the capillary pressure, the equation reduces to [4].

$$f_w = \frac{1}{1 + \frac{k_{ro}\mu_w}{k_{rw}\mu_o}} \tag{9}$$

The properties of oil and water are shown in Table I.

TABLE I
THE PHYSICAL PROPERTY OF OILS AND WATER

Properties	Light oil	Heavy oil	Water
Density ρ (g/cm^3)	0.795	0.9837	1.00
Viscosity μ(Pa · s)	0.00242	0.0167	0.001

Table II and Fig. 2 show the changing in relative permeability and fractional water flow for the displacement of heavy oil by water. The relative permeability of water calculated which becomes very small even though water flow occurs together with flow through sand.

TABLE II
RELATIVE PERMEABILITY AND FRACTIONAL FLOW RATE OF HEAVY OIL

S_w	k_{rw}	k_{ro}	f_w	f'_w
0.12	0	0.95	0.00	
0.17	0.001	0.77	0.178	0.28
0.18	0.01	0.64	0.207	0.34
0.24	0.02	0.54	0.382	0.34
0.28	0.03	0.45	0.527	0.27
0.34	0.03	0.36	0.582	1.09
0.44	0.04	0.27	0.712	0.96
0.50	0.04	0.19	0.779	0.89
0.60	0.05	0.10	0.893	0.87
0.73	0.06	0.00	1.000	0.00

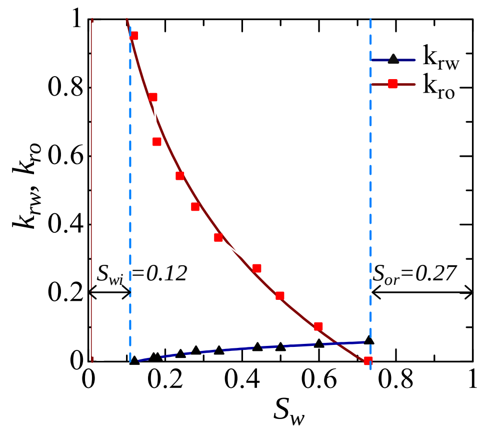

Fig. 2 Relative permeability curve of heavy oil

Laboratory data have normally summarized the characteristic of relative permeability of heavy oil and water. The relative permeability curves have displayed the tendency and behavior of heavy and water, where the heavy oil is a non-wetting phase and water is a wetting phase, which is illustrated in Fig. 2.

IV. Fractional Flow of Heavy Oil

The shape of the fractional flow curve at various water saturation is characteristically S-shape. The limits of the curve (0 and 1) are defined by the end points of the relative permeability curves.

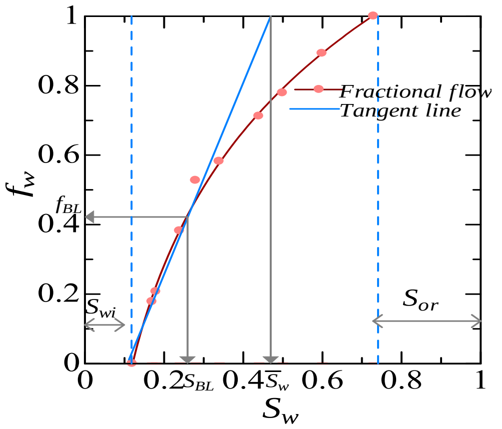

Fig. 3 Fractional flow curve of heavy oil

TABLE III
Data of Relative Permeability and Fractional Flow of Light Oil

S_w	k_{rw}	k_{ro}	f_w	f'_w
0.165	0	1	0	
0.2	0.0001	0.848108	0.00012	0.003423
0.3	0.00583	0.500364	0.01152	0.113997
0.4	0.03076	0.263648	0.104474	0.929545
0.5	0.0891	0.116607	0.433144	3.286695
0.6	0.19508	0.037892	0.837357	4.042131
0.7	0.36292	0.006149	0.983339	1.45982
0.8	0.60684	2.85E-05	0.999953	0.166145
0.82	0.666	1.09E-47	1	0.002346

The fractional flow curve is not very satisfied by drawing a tangent line. However, that begins at $S_w=S_{wi}$ and $f_w=0$, having a point of the tangent at $S_w=S_{wf}$ and $f_w=f_{wf}$, and ultimately extrapolated to intersect the line $f_w=1$ the point of intersection representing $\bar{S}_w$. Finally, at breakthrough, the shock front arrives at $x=L$ and the water saturation at the outlet equals S_{wf}. Furthermore, in order to obtain the water saturation at the outlet after breakthrough, tangents can be constructed to the fractional flow curves for water saturation greater than S_{wf} [5], [6].

V. Relative Permeability of Light Oil

The features of the relative permeability curves and the characterization of two immiscible fluid flow are controlled by fluid properties and rock types, and its appropriate explanation helps engineers to establish confident predictions from the waterflooding calculation. The relative permeability is usually expressed by the ratio of effective permeability to absolute permeability and the effective permeability is less than absolute permeability. Therefore, the value of relative permeability less than one.

The relative permeability and fractional flow data are shown in Table III. Generally, the relative permeability between two immiscible phases (light oil and water) during the process are shown in Fig. 4. When wetting and non-wetting phase flow together in a sample, each phase follows separate and distinct paths.

The wetting phase is more attractive to coat the grain of rocks. Therefore, the relative permeability values of wetting phase are smaller than a non-wetting phase. The characteristic feature of relative permeability curves illustrates that the wetting phase is water and non-wetting phase is light oil. However, a small non-wetting phase saturation will drastically reduce the wetting phase permeability [6], [7].

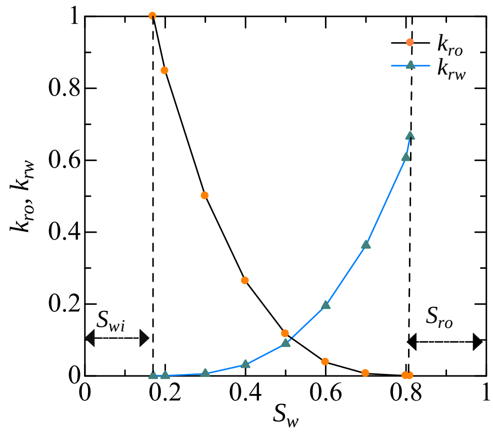

Fig. 4 Relative permeability curve of Light oil

VI. Fractional Flow of Light Oil

The fractional flow curve for light oil is illustrated in Fig. 5.

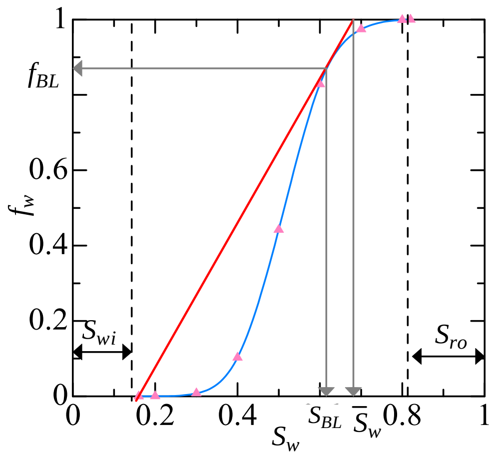

Fig. 5 Fractional flow

The fractional flow curve is completely matching to the tangent line, illustrated in Fig. 5. From the tangent line, one can find out the average saturation ($\bar{S}_w = 0.70$) and frontal flow saturation ($S_{BL} = 0.63$). Irreducible water saturation is obtained ($S_{iw} = 0.16$) and the residual oil is ($S_{ro} = 0.18$).

VII. Conclusion

In heavy oil systems, the flow characteristics are different with light oil system. The test of relative permeability in imbibition process (displacement of heavy oil by water) performs in with different saturation ratios of heavy oil and water. The curves of relative permeability of heavy oil and water display the behavior of simultaneously flow in sands. While the water saturation gradually increasing, the relative permeability curve of heavy oil rapidly decreases until the saturation of water reaches to 82%. At the end point of relative permeability of water, only residual oil 18% remains into pores which cannot flow anymore. In addition, the start point of the curve of relative permeability of water shows the irreducible water in the reservoir. Furthermore, according to this experimental analysis, the irreducible water is 16.5% which cannot flow.

The curves of relative permeability of heavy oil and water show the relation between wetting phase and non-wetting phase.

Finally, the displacement of oil by water in petroleum reservoir is analyzed using the famous Buckley-Leverett frontal displacement theory. The effect of relative permeability on displacement efficiency is investigated through the analysis. The major results obtained from this study are as follows:

1. According to the theory, the fractional flow rate of water, i.e. the fraction of pore water flow through displacement, is given by a function of the ratios of the viscosity of two liquids and relative permeabilities to the reservoir, if capillary pressure and gravitational effect are neglected.
2. Advance of constant saturation front, S_{wf} can be calculated using the derivative of fractional flow function with respect to water saturation. The average saturation behind the front is obtained by the derivatives and irreducible water saturation.
3. Relative permeability has an insignificant effect on the progress of saturation front, as determined by changing the endpoint value for water permeability. The maximum differences in the water saturation at the front,S_{BL}, and the average water saturation behind the front,$\bar{S}_w$, are found to be about 7% (Fig. 5).
4. Fractional flow curve of light oil is characteristically S shape and matches with the tangent line. The front flow saturation is $S_{BL} = 0.63$. Therefore, a huge amount light oil might be displaced by water. But unfortunately, the fractional flow curve of heavy oil is not matching with tangent of the curve and the curve is not characteristically S shape. The front flow saturation is very less $S_{BL} = 0.28$. Therefore, the displacement of heavy oil by water is not suitable.

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