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Study of Dynamic Viscosity Ratio Effectiveness on Linear Displacement of Fluid Flow

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Abstract: Immiscible fluid displacement through a porous medium has many critical applications, such as oil recovery from reservoirs by water injection. These processes are controlled by many important factors such as oil and water relative permeability and fluid viscosity. This research's primary objective is to study the performance of displacing fluid (water) to displace oil depending on the water to oil viscosity and relative permeability. Analytical works based on fractional flow equations have been used with different viscosity ratios and mobility ratios, as the displacing fluid's viscosity is necessary for oil recovering operations. The following data are required in this study, and they are obtained from one Iraqi oil field from a limestone reservoir. The relative permeability ratio for water-oil flow is water saturation in the porous medium used and the water-oil viscosity ratio. In this study, fractional flow equations are derived, and water cut is calculated and plotted versus water saturation for different cases of viscosity ratio μo/μw. Other parameters such as mobility ratio, average water saturation at breakthrough, and endpoint of relative permeability are calculated for accomplishing the study.

Keywords: *immiscible displacement, mobility ratio, oil recovery, linear displacement, fractional flow, flow in porous media.*

1. Introduction

Oil is produced from a reservoir as a second stage when displaced by water. Water displaces oil from pores in an ideal case through a piston-like displacement or a leaky piston displacement. However, due to the variety of wet conditions, the water relative permeability and oil are critical in deciding where each fluid flows and how hydrocarbon is displaced by water. Additionally, the crude oil viscosity is greater than that of water, resulting in non-ideal displacement behavior [1-3]. Conditions such as viscosity, initial fluid saturation, capillary, and gravitational effects influence the magnitude of initial displacement phases. The more viscous the hydrocarbon, the more difficult it is for it to flow through pores rocks. Increased oil viscosity thus results in a more residual oil saturation remain during the displacement [4].

Capillary forces tend to be effective against the creation of saturation discontinuities in homogeneous sand. In contrast, gravitational forces favor the complete vertical separation of oil and water. Thus, in any reservoir where water is rising to displace oil, the capillary and gravitational forces oppose one another and appear to balance out somewhat [5]. At high displacement rates, frictional forces surpass both, masking their effects and allowing the flow to be governed mainly by relative permeabilities and viscosities. However, at meager displacement rates, frictional forces are negligible, and the saturation distribution is determined by combining capillary and gravitational forces [6]. When water influx the reservoir due to oil extraction, the degree of zero capillary pressure increases, creating a tendency for water saturation to increase in the reservoir to achieve a new equilibrium of capillary pressure and gravity [7].

The primary purpose of this study is to study the impact of water to oil viscosity on oil displacement by water. Analytical works based on fractional flow equations have been applied to various cases involving mobility ratios, fluid displacing efficiency, and oil and water processing. The displacing fluid's viscosity aids in oil recovery.

2. Fractional Flow Equation Derivation

The fractional water flow, fw, is represented by the flow rate of water q_w to the total flow rate [8], or:

$$f_w = \frac{q_w}{q_t} = \frac{q_w}{q_w + q_o} \quad and \quad q_w = f_w q_t \tag{1}$$

Where;
f_w = water fraction (or water cut)
q_t (bbl/day) = flow rate of water and oil.
q_w (bbl/day) = flow rate of water.
q_o (bbl/day) = flow rate of oil.

The steady-state flow of two immiscible fluids such as oil and water, Darcy's equation is used to determine the flow of each fluid as [8-9]:

$$q_o = \frac{-AK_o}{\mu_o}\left[\frac{\partial P_o}{\partial x} + g\rho_o \sin(\emptyset)\right] \tag{2}$$

$$q_w = \frac{-AK_w}{\mu_w}\left[\frac{\partial P_w}{\partial x} + g\rho_w \sin(\emptyset)\right] \tag{3}$$

Where;
k_o, k_w = oil effective permeability, and water effective permeability.
μ_o, μ_w = oil viscosity and water viscosity.

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P_o, P_w = oil pressure and water pressure.

ρ_o, ρ_w = oil and water density.

A = area.

x = distance.

$\emptyset$ = dip angle.

$\sin(\emptyset)$ = up-dip flow is positive, whereas down dip flow is negative.

Rearranging and subtracting equations 2 and 3 produces:

$$\frac{q_w\,\mu_w}{AK_w} - \frac{q_o\,\mu_o}{AK_o} = \left(\frac{\partial P_o}{\partial x} - \frac{\partial P_w}{\partial x}\right) - g(\rho_w - \rho_o)\sin(\emptyset) \qquad (4)$$

From the definition of the capillary pressure: $P_c = P_o - P_w$And differentiating it for the distance x gives [8]:

$$\frac{\partial P_c}{\partial x} = \frac{\partial P_o}{\partial x} - \frac{\partial P_w}{\partial x} \qquad (5)$$

Combining Eq 4 with 5 gives:

$$\frac{q_w\,\mu_w}{AK_w} - \frac{q_o\,\mu_o}{AK_o} = \frac{\partial P_c}{\partial x} - g\Delta\rho\sin(\emptyset) \qquad (6)$$

Replacing oil flow rate qo and water flow rate qw in Eq 6 with qo and qw of Eq 1 yields:

$$f_w = \frac{1 + \left(\frac{AK_o}{q_t\,\mu_o}\right)\left[\frac{\partial P_c}{\partial x} - g\Delta\rho\sin(\emptyset)\right]}{1 + \frac{K_o\mu_w}{K_w\mu_o}} \qquad (7)$$

For a horizontal reservoir, i.e., $\sin(\Phi) = 0$, the injection rate does not affect the fractional flow curve, and Eq 7 is reduced to the following form [8-9]:

$$f_w = \frac{1}{1 + \frac{K_{ro}\ \mu_w}{K_{rw}\ \mu_o}} \qquad (8)$$

Due to the broad range of possible values, the relative permeability ratio plotted on semi-log paper using the log scale [10-11]. The relative permeability ratio versus water saturation is expressed as a straight line by [10]:

$$\frac{K_{ro}}{K_{rw}} = ae^{bS_w} \qquad (9)$$

The constants "a" and "b" calculated by plotting Kro/krw versus saturation on semi-log paper or solving simultaneous equations using known saturation and relative permeability values. Substituting Eq. 9 into Eq. 8 will end with:

$$f_w = \frac{1}{1 + \left(\frac{\mu_w}{\mu_o}\right)ae^{bS_w}} \qquad (10)$$

Differentiating the preceding equation for Sw results in the following:

$$\left(\frac{df_w}{dS_w}\right)_{sw} = \frac{-\left(\frac{\mu_w}{\mu_o}\right)a\,b\,e^{bS_w}}{\left[1 + \left(\frac{\mu_w}{\mu_o}\right)ae^{bS_w}\right]^2} \qquad (11)$$

The ratio $(df_w/dS_w)_{Sw}$ is the first derivative or slope of the fractional flow curve.

3. Methodology and Results

3.1. Determination of Wetting Phase

When a nonwetting phase and a wetting flow concurrently through the reservoir's rock, each phase takes a distinct and separate direction; the two phases' distribution is different. Various relative permeabilities result for nonwetting and wetting phases due to the two phases' distribution according to wetting physical characteristics. Low saturation of the wetting phase fills the smaller pore and doesn't contribute to fluid flow. However, the nonwetting phase fills large pores and contributes significantly to fluid movement through the reservoir. According to relative permeability curves in Fig 1, the reservoir is slightly oil-wet. This is because the curve's intersection is less than 0.5 of k_{rw}.

3.2. Fractional flow calculations

After obtaining the relative permeabilities of oil and water, it is essential to determine fractional water flow for various viscosity ratios μo/μw, utilizing the fractional flow equation (Eq. 10). The constants "a" and "b" in Equation 10 are determined from the relative permeability ratio (k_{ro}/K_{rw}) versus water saturation (Sw) plotted on a semi-log paper, as shown in Fig 2. The coefficients "a" and "b", in this study, are determined to be; a = 133.61 and b = -9.874 with R^2 = 0.9763. When the water cut (fw) is plotted against the water saturation (Sw), an S-shaped curve results, as shown in Fig 3 through Fig 5. By substituting for '*a*' and '*b*,' the fractional flow curves are plotted as shown in Fig. 3 through Fig. 5, that used to find average water saturation at the breakthrough $\overline{SwBT}$ for each corresponding $\mu o/\mu w$ ratio. To determine $\overline{SwBT}$ A straight line drawn from initial water saturation (Swi) and tangent to the upper part of the curve intersect with the y-axis at FW =1 to find average water saturation behind the waterfront for each $\mu o/\mu w$ case as shown in Table (1).

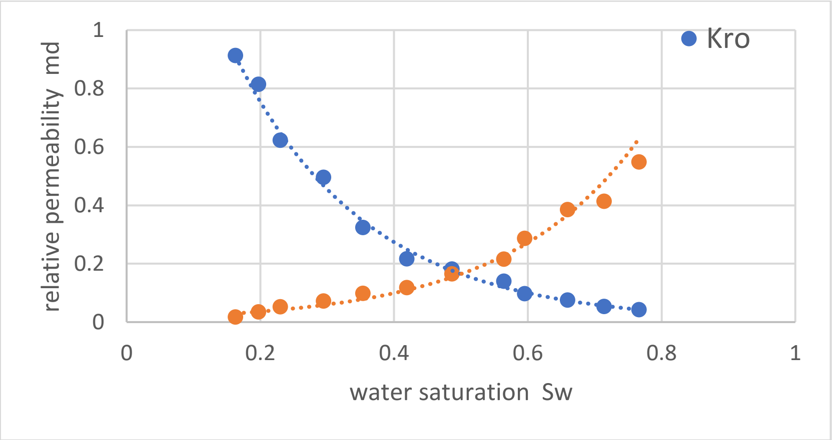

Fig. 1: Oil and water relative permeability curves

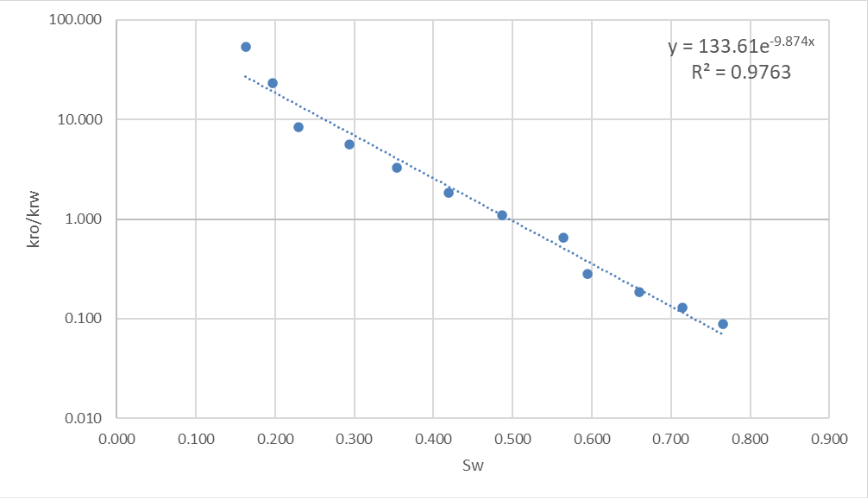

Fig. 2: relative permeability ratio vs. Sw semi-log plot

Table 1: Average Water Saturation Behind Flood Front $\overline{Sw}$

μw/ μo	$\overline{SwBT}$
0.674	0.716
0.456	0.657
0.295	0.593

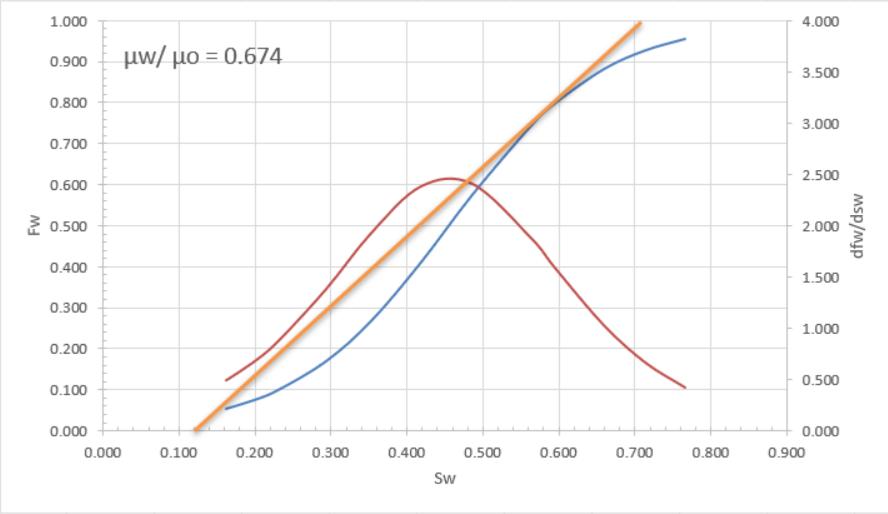

Fig. 3: Fractional flow curve (μo/μw = 0.674)

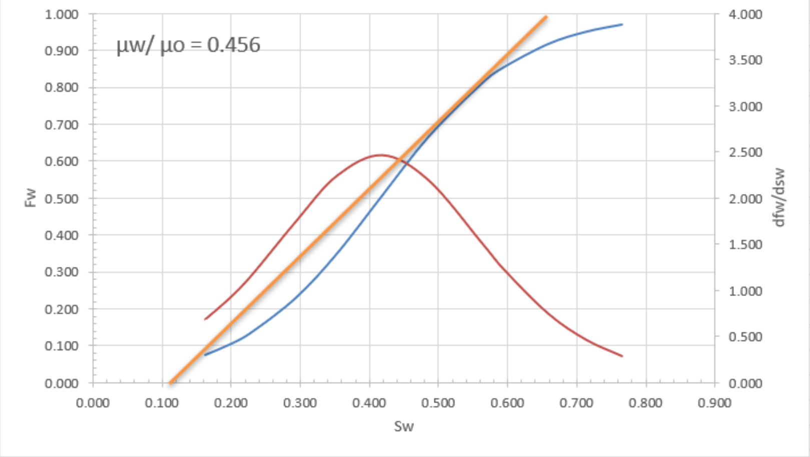

Fig. 4: Fractional flow curve (μo/μw = 0.456)

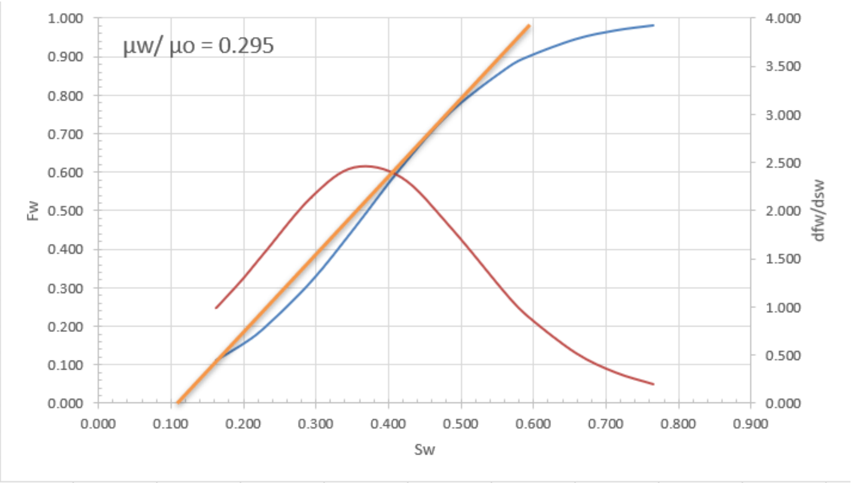

Fig. 5: Fractional flow curve (μo/μw = 0.295)

3.3 Mobility ratio calculation

The mobility ratio, essentially, is the ratio of displacing phase's mobility to the displaced or resident phase's mobility [12].

$$M = \frac{K_{rw}}{K_{ro}} \frac{\mu_o}{\mu_w} \qquad (12)$$

Mep is mobility ratio, *krw* is water relative permeability, and *kro* is oil relative permeability. The mobility ratio (*Mep*) is the function of viscosity and relative permeability, both of which are saturation-dependent. A mobility ratio variation is Craig's mobility ratio - ***Mc***, and defined as [13-15]:

$$M_c = \frac{K_{rw}\,(\overline{SwBT})}{K_{ro}(S_{wi})} \frac{\mu_o}{\mu_w} \qquad (13)$$

Where $K_{rw}\,(\overline{SwBT})$ is the relative permeability of water at the average saturation at the breakthrough and $K_{ro}(S_{wi})$ is the relative permeability of oil at the initial water saturation.

Using these values, we measure Craig's mobility ratio for each viscosity ratio using Eq. 13, as shown in Table 2.

Table 2: mobility ratio determination results

μw/ μo	$\overline{SwBT}$	Krw @ $\overline{SwBT}$	Kro @ Swi	Mc
0.674	0.716	0.416	0.921	0.669
0.456	0.657	0.382	0.921	0.911
0.295	0.593	0.283	0.921	1.042

4. Discussion

In Case 1, the estimated water saturation estimated at the breakthrough is 0.716 based on the fractional flow curves. According to the fractional flow curve (Fig. 3), the viscosity ratio of 0.674 with a mobility ratio of 0.669 has a more effective displacement operation. The curve is moved slightly lower, resulting in a lower water fraction value. Reduced water fractional value increases in fractional oil value, which results in increased oil mobility, which results in a more fluid displacement process that is highly effective.

In Case 2, water saturation is estimated at the breakthrough as 0.657 based on the fractional flow curves. According to the fractional flow curve (Fig. 4), the viscosity ratio of 0.456 with a mobility ratio of 0.911 has a less effective displacement mechanism than case 1. The curve is moved slightly upward from case 1, resulting in a more excellent value of water fraction. Increased water fractional value decreases fractional oil value and thus oil mobility, resulting in a lower fluid displacement efficiency.

In Case 3, the water saturation was estimated at the breakthrough as 0.593 based on the fractional flow curve. According to the fractional flow curve (Fig. 5), the viscosity ratio of 0.295 with a mobility ratio of 1.042 has the least displacement efficiency from case 1 and case 2. The curve is moved upward, resulting in a more significant water fraction value. Increased water fractional value decreases fractional oil value and oil mobility, resulting in the least efficient fluid displacement. Fig.6 illustrates a comparison of three fractional flow curves of varying mobility ratio values. As seen in the graph, the water viscosity (which affects the value of the mobility ratio) affects the form of the fractional flow curve.

Reduced water viscosity resulted in an increase in water fraction, which shifted the curve positively upward. If the fractional flow curve moves upward, the displacement process becomes less efficient. This is because an increase in the water fraction results in a decrease in the oil fraction and mobility.

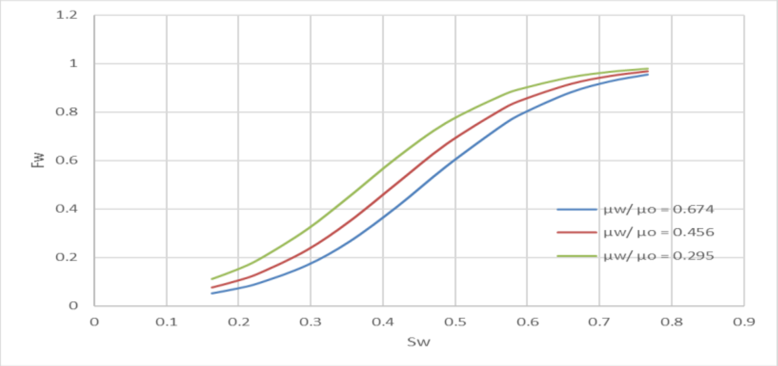

Fig. 6: Comparison between fractional flow curves of three cases

Reduced oil mobility means the oil has less freedom to travel, which affects the waterflooding process because the injected water has a difficult time dislodging the oil with low mobility. As a consequence, the least effective displacement process occurs, resulting in lower oil recovery. From these cases, we see that the displacing fluid's viscosity is critical to the displacement phase. For case 1 (mobility ratio of 0.669) with a viscosity of 3.18 cp, the displacement mechanism is significant because the displacing fluid has a higher viscosity than oil, a viscosity of 4.715 cp. Due to the viscosity difference, these conditions allowed the water to flow behind the oil. If the displacing fluid has a lower viscosity than the displaced fluid, as in case 3, the displacement mechanism is inefficient. The low viscosity water flows bypass through the oil, reducing the amount of oil that be displaced.

5. Conclusions

The fractional flow curve with a low mobility ratio and a high water-oil viscosity ratio is moved down slightly, resulting in a lower water fraction value. Reduced water fractional value increases in fractional oil value, which results in increased oil mobility, which results in a more efficient fluid displacement process. The mobility ratio has an impact on the production of oil. A low mobility ratio results in high oil production at the expense of water production, while a high mobility ratio results in increased water production relative to oil production. Reduced water viscosity resulted in an increase in water fraction, which shifted the curve positively upward. Increased water fractional value decreases fractional oil value and thus oil mobility, resulting in a less efficient fluid displacement operation. Reduced oil mobility means the oil has less freedom to travel, which affects the waterflooding process because the injected water has a difficult time dislodging the oil with low mobility. As a consequence, the least effective displacement process occurs, resulting in less oil recovery. From these cases, we see that the displacing fluid's viscosity is critical to the displacement phase.

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