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ANALYSIS OF FRACTIONAL FLOW AND RELATIVE PERMEABILITY OF HEAVY OIL AND KEROSENE DURING RECOVERY IN PETROLEUM RESERVOIR

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ABSTRACT: This paper evaluates and compares the effect of fractional flow and relative permeability of heavy oil and Kerosene during recovery in a petroleum reservoir. Water fingering is one of the challenging problems during oil recovery and another comprehensive problem is, to exactly evaluate the amount of recover oil from a petroleum reservoir. To address these problems, the fractional flow and relative permeability of heavy oil and Kerosene are analyzed. The fractional flow approach is originated in the petroleum engineering literature and employs the saturation of one of the phases and a pressure as the independent variables. The fractional flow approach treats the multi-phases flow problem as a total fluid of a single mixed fluid and then describes the individual phases as fractional of the total flow. Laboratory steady state flow experiments are performed in two different types of oils (Heavy oil and Kerosene), to empirically obtain relative permeability and fractional flow curves, which have great influence in recovery efficiency calculation. Therefore, the famous Buckley-Leverett displacement mechanism has been used to calculate the performance of waterflooding. With Buckley-Leverett method, oil recovery from waterflooding is calculated and required water injection volume to achieve that oils recovery are estimated for heavy oil, which the total amount of oil produced up to the breakthrough is $A\ \varphi\ B\ \times RF$ = 15901.92 m^3 (= 99864.05 barrels) and for Kerosene is $A\ \varphi\ B\ \times RF$ = 24992.06 m^3 (156950.16 barrels). Additionally, the front flow of heavy oil is approximately spread to 80 m, and the front flow of light oil is approximately spread to 300 m. As a result indicates that fractional flow theory predicates a stable frontal displacement of all mobility ratios contrary to observed experimental facts. Therefore, fractional flow theory is suitable for describing the performance of stable displacement of oils by water.

Keywords: Fractional Flow, Relative Permeabilities of Oils and Water, Oil Recovery and Water-fingering, Average saturation

1. INTRODUCTION

In petroleum reservoir engineering, a technique of injecting water into oil reservoir has been used in order to maintain oil production rates during the pumping operation shown in Fig1. The method is known as the waterflooding technique, which provides a high oil production rates and a high degree of petroleum recovery when oil production rates deteriorate [1]. Due to applying the waterflooding technique in a petroleum reservoir, the analyzing of fractional flow of water and relative permeability of oil and water are the most important.

There are two different methods to measure the relative permeability, steady state method aims to achieve the steady-state flow at different fractional flow ratios yielding unique core saturation at each ratio. The results are easy to interpret; however, it takes a long time to achieve steady-state conditions. In traditional unsteady-state methods, the core saturated with oil is flooded by water at constant total rate until no more oil is produced.

The steady state method is used in this paper for measuring of relative permeability. Firstly, the relative permeabilities of oils and water are analyzed, then the fractional flow, average saturation, and front flow saturations are determined. After analyzing, the results of fractional flow, relative permeabilities of oils and the amount of recovery oils are compared during 300 days.

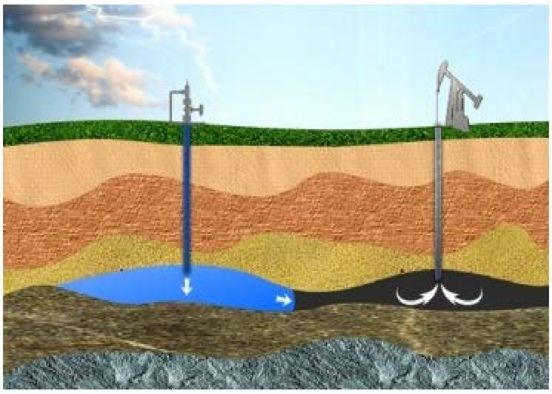


Fig.1 Waterflooding technique in petroleum reservoir [2].

The fractional flow approach originated in the petroleum engineering literature and employs the saturation of one of the phases and a pressure as the independent variables. The fractional flow approach treats the multi-phases flow problem as a total fluid of a single mixed fluid and then describes the individual phases as fractional of the total flow [3].

Furthermore, during the laboratory experiments, the fractional flow ratio is recorded, as well as the pressure at both ends and the breakthrough time of the injected fluid. The two-phase relative permeability, as a function of saturation at the effluent end of the core, can then be determined based on the fractional flow theory. Therefore, relative permeabilities of oil and water as mentioned mostly depends on the saturation of water [4].

From the definition of fractional flow, which is illustrated in Fig 2.

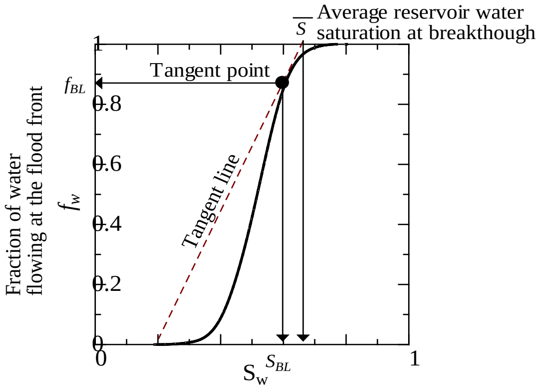


Fig.2 Fractional flow curve

That the limits of the fractional flow are different from 0 to 100%. At the irreducible water saturation, the water flow rate is zero and, therefore, fractional flow is zero percent. At the residual oil saturation point, the oil flow rate is zero and the fractional flow reaches it's to the upper limit of 100%. The shape of the fractional flow at various water saturation curve is characteristically S-shape, shown in Fig 2. The limits of the curve (0 to 1) are defined by the end points of the relative permeability curves.

2. BUCKLEY LEVERETT ANALYSIS

Derivation of the fractional flow equation for the one-dimensional oil-water system by considering of displacement of oil by water in a system of dip angle α [5].

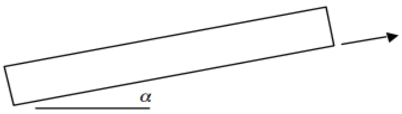


Fig.3 One dimensional oil-water flow system.

It starts with Darcy's equations

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

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

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

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

After rearranging, the equations may be written as:

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

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

Subtracting the first equation from the second one can get,

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

Substituting for

$$q_T = q_w + q_o \quad (7)$$

Fractional flow of water as

$$f_w = \frac{q_w}{q_o} \quad (8)$$

And solving for the fractional flow of water, the following expression can be obtained for the fractional flow of water:

$$f_w = \frac{1+\dfrac{k\,k_{ro}\,A}{q_T\,\mu_o}\left(\dfrac{\partial p_{cow}}{\partial x}-\Delta\rho\,g\sin\alpha\right)}{1+\dfrac{k_{ro}}{\mu_o}\dfrac{\mu_w}{k_{rw}}} \qquad (9)$$

For the simplest case of horizontal flow, with negligible capillary pressure, the expression reduces to:

$$f_w = \frac{1}{1+\dfrac{k_{ro}}{\mu_o}\dfrac{\mu_w}{k_{rw}}} \qquad (10)$$

2.1 Derivation of the Buckley-Leverett equation

For a displacement process where water displaces oil, the derivation should start with the application of a mass balance of water around a control volume of length of in the following system for a time period of Δt [6], [7]:

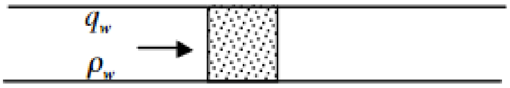


Fig.4 Mass balance system.

The mass balance may be written:

$$\begin{aligned}&\left[(q_w\rho_w)-(q_w\rho_w)_{x+\Delta x}\right]\Delta t\\&=A\Delta x\phi\left[(S_w\rho_w)^{t+\Delta t}-(S_w\rho_w)\right]\end{aligned} \qquad (11)$$

Which reduces to the continuity equation $\Delta x \to 0$, when and: $\Delta t \to 0$

$$-\frac{\partial}{\partial x}(q_w\rho_w) = A\phi\frac{\partial}{\partial t}(S_w\rho_w) \qquad (12)$$

let us assume that the fluid compressibility may be neglected, $\rho_w = constant$

Also, can be written that

$$f_w q_w = q_T \qquad (13)$$

Therefore

$$-\frac{\partial f_w}{\partial x} = \frac{A\phi}{q_T}\frac{\partial S_w}{\partial t} \qquad (14)$$

Since the equation may be rewritten as;

$$-\frac{\partial f_w}{\partial S_w}\frac{\partial S_w}{\partial x} = \frac{A\phi}{q_T}\frac{\partial S_w}{\partial t} \qquad (15)$$

This above equation is known as the Buckley-Leverett equation.

2.2 Derivation of the frontal advance equation

Since $S_w(x,t)$ can write the following expression for saturation change

$$dS_w = \frac{\partial S_w}{\partial x}dx + \frac{\partial S_w}{\partial t}dt \qquad (16)$$

In the Buckley-Leverett solution, a fluid front of constant saturation can be followed during the displacement process; thus:

$$0 = \frac{\partial S_w}{\partial x}dx + \frac{\partial S_w}{\partial t}dt \qquad (17)$$

Substituting into the Buckley-Leverett equation and get

$$\frac{dx}{dt} = \frac{q_T}{A\phi}\frac{df_w}{dS_w} \qquad (18)$$

Integration in time

$$\int_t \frac{dx}{dt}\,dt = \int_t \frac{q}{A\phi}\frac{df_w}{dS_w}\,dt \qquad (19)$$

Yields an expression for the position of the fluid front:

$$x_f = \frac{q}{A\phi}\left(\frac{df_w}{dS_w}\right)_f \qquad (20)$$

Which is often called the frontal advance equation.

3. LABORATORY EXPERIMENTS

The laboratory state steady flow experiments are performed for measuring relative permeability and fractional flow. The experiments are concentrated in two different types of oils (Kerosene and heavy oil), the properties of these oils and water are shown in, Table1 [8].

Table 1 Physical properties of oils and water

Properties	Kerosene	Heavy oil	water
Density ρ	0.795	0.837	1.00
Viscosity μ	0.00242	0.0167	0.001

The procedure of this experiment, firstly, the sand samples are saturated by oil, then the oil and water are simultaneously pumped into different ratios. The experiment starts with a high ratio of oil and a low ratio of water. The components of apparatus are illustrated in Fig 5.

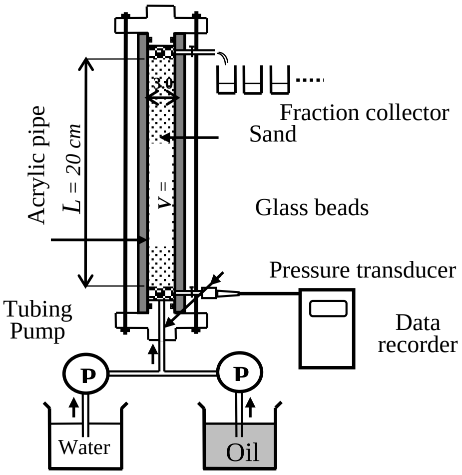


Fig.5 Apparatus for measuring of relative permeabilities.

Toyoura standard sand is used in experiments, where the diameter of sand is (0.105-0.425) mm, the density is $\rho_s = 2.65$ gr/cm^3. The length of the sample is 20 cm and the diameter of the sample is 7.065cm^2.

3.1 Relative permeability of heavy oil

It is easily expected that permeability to either fluid to be lower than that for the single fluid since it occupies only part of the pore space and may also be affected by interaction with other phases. The concept used to address this situation is called relative permeability. The relative permeability of heavy oil k_{ro} is defined as:

$$k_{ro} = \frac{k_{eo}}{k} \tag{21}$$

The relative permeability of water k_{rw} is defined as:

$$k_{rw} = \frac{k_{ew}}{k} \tag{22}$$

The effective permeabilities of fluid can be determined where two or three phases of fluid oil and water or oil, water and gas are simultaneously flow based on the Darcy's law.

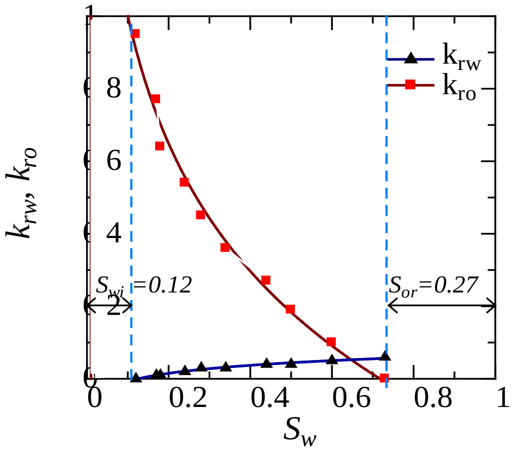
Heavy oil is displaced by injected water. Therefore, the heavy oil saturation decreasing and the water saturation increasing. The desaturation of oil continues until the residual oil saturation is achieved $S_{ro} = 0.27$, the data is shown in Table 2.

Table 2 Relative permeability and fractional flow

S_w	k_{rw}	k_{ro}	f_w	f'_w
0.12	0.00	0.95	0.00	
0.17	0.01	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

Laboratory data are 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 6.

Fig.6 Relative permeability of heavy oil



3.2 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 (0and 1) are defined by the end points of the relative permeability curves. The fractional flow curve is illustrated in Fig 7.

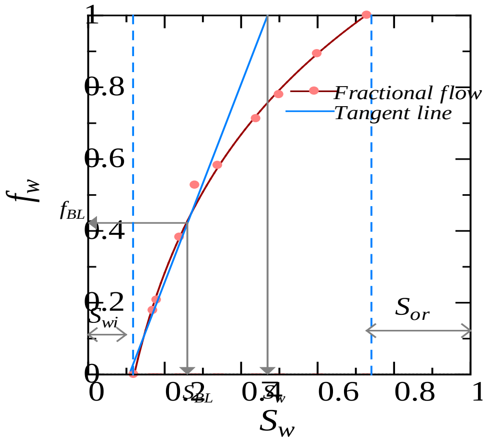


Fig.7 Fractional flow of water

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} [9].

3.3 Relative permeability of Kerosene

The fractional flow and relative permeability of oil and water are obtained differently. Because, the relative permeability and fractional flow value and characterization are controlled by rock types and fluid properties, and its appropriate description helps engineers to make confident predictions from the waterflooding calculation. The relative permeability and fractional flow data are shown in Table.3.

Table 3 The data of fractional flow of water and relative permeability of kerosene.

S_w	k_{rw}	k_{ro}	f_w	f'_w
0.16	0.000	1.000	0.000	0.000
0.20	0.000	0.886	0.000	0.008
0.30	0.005	0.578	0.021	0.114
0.40	0.027	0.269	0.10	0.929
0.50	0.028	0.116	0.433	3.286
0.60	0.182	0.036	0.837	4.042
0.70	0.344	0.005	0.983	1.499
0.80	0.581	0.000	0.999	0.166
0.82	0.610	0.000	1.000	0.002

Generally,the relative permeability between two immiscible phases (kerosene and water) during the operation are illustrated in Fig 8. When wetting and non-wetting phase flow together in a reservoir rock, each phase follows separate and distinct paths.

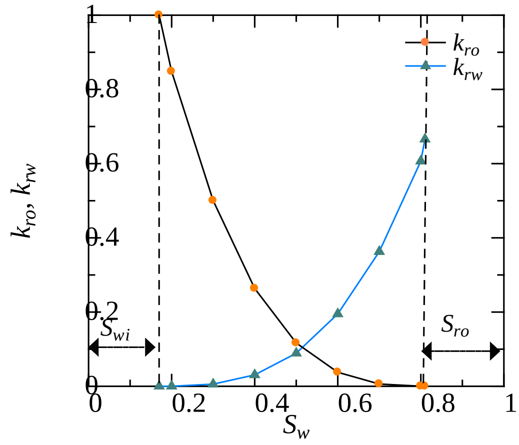


Fig.8 Relative permeability of Kerosene

The distribution of the two phases according to their wetting characteristics results in characteristic wetting and non-wetting phase relative permeabilities. Since the wetting phase occupies the smaller pore openings at small saturations, and these pore openings do not contribute materially to flow, it follows the presence of a small wetting phase saturation will affect the non-wetting phase permeability only to a limited extent. Since the non-wetting phase occupies the central or larger pore openings which contribute materially to fluid flow through the reservoir. However, a small non-wetting phase saturation will drastically reduce the wetting phase permeability [10].

3.3 Fractional flow of Kerosene

The fractional flow curve for Kerosene is shown below.

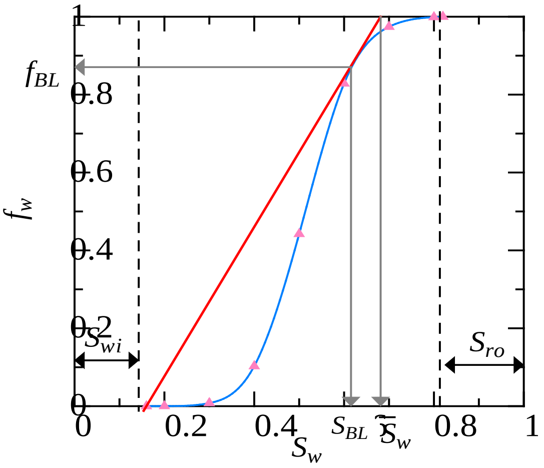


Fig.9 Fractional flow of water

The fractional flow curve completely matching at the tangent line and easy can find out the average saturation ($\overline{S}_w$ = 0.70) and frontal flow saturation (S_{BL} = 0.63). Irreducible water saturation is obtained (S_{wi} = 0.16) and the residual oil is (S_{ro} = 0.18).

4. WATERFLOODING TECHNIQUE

In this phenomena, the displacing fluid (water) is injected into a petroleum reservoir to improve oil production [11], [12]. According to equation (20), each saturation advances into the system at rate in direct proportion to, $f'_w = df_w / dS_w$

The amount of oil produced can be calculated as follows.

$$\begin{aligned} dx/B &= f'_w q_T \, dt / A\phi B \\ &= f'_w q_T \, dt / V_p = f'_w dV_p \end{aligned} \tag{23}$$

Where $V_p = A\phi B$ is the pore volume of the reservoir and dV_p is the volume of water injected in units of pore volume. Since the saturation in equation (23) is constant, the equation can be integrated:

$$x = Bf'_w dV_p \tag{24}$$

The oil recovery factor for this situation may be computed as:

$$RF = \frac{\overline{S}_w - S_{wi}}{1 - S_{wi}} \tag{25}$$

4.1 Waterflooding technique for heavy oil

As a quantitative demonstration for the Buckley-Leverett analysis, for recovering of heavy oil from petroleum reservoir where the extent area $A = 18000$ m^2, thickness $B = 15$ m, porosity $\phi = 0.18$ is considered. The relative permeability data shown in Table 2 and Table 3 is applied here, and viscosity of water and oils are shown in Table1. The total amount of water injected is $q_T = q_w = 800\, m^3 / day$. The water saturation at the front and the average saturation behind the front are found through the graphic method to be $S_{BL} = 0.32 \, and \, \overline{S}_w = 0.48$

Fig.10 illustrates the calculated results of saturation profile by Buckley-Leverett analysis. It is seen that the saturation front progresses with a constant speed toward upward, and breakthrough at t = 300 days. The heavy oil recovery factor is calculated from (25) and found to be $RF = 0.409$, from which the total amount of oil produced up to the breakthrough is $A \varphi B \times RF$ = 15901.92 m^3 (= 99864.05 barrels) for the given reservoir. Since oil recovery factor includes residual oils, the recovery factor of produced oil to displaceable oil in the reservoir may be calculated by,

$$RFD = \frac{\overline{S}_w - S_{wi}}{1 - S_{wi} - S_{ro}} \tag{26}$$

and the value is 0.82. The remaining 0.18 displaceable oil could be withdrawn after the breakthrough by waterflooding, but water-cut, the ratio of water produced compared to the volume of total liquids produced, will significantly increase.

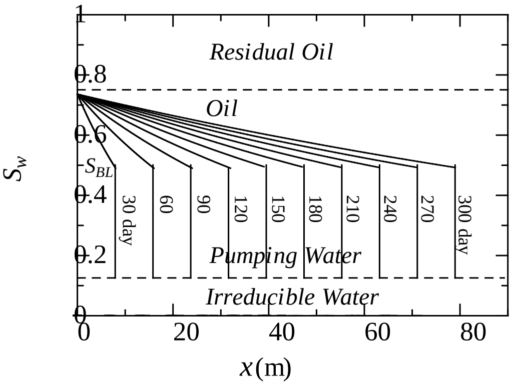


Fig.10 Displacement results of heavy oil by Buckley-Leverett

Heavy oil reservoirs contain oil that does not flow easily under reservoir conditions which means the successful recovery of this resource is based upon developing a mechanism that displaces the heavy oil in the reservoir. Goodarzi et al., (2009) define heavy oil in terms of viscosity as the class of oils ranging from 50 cP to 5000 cP. The high viscosity restricts the easy flow of oil at the reservoir condition [13]. Kumar (2006) reported incremental recovery of approximately 2 to 20% of the original oil in place [14]

However, there are different parameters to effect on displacement process. Therefore, the heavy oil recovery by waterflooding technique is less than Kerosene.

4.2 Waterflooding technique for Kerosene

The waterflooding technique is also applied for displacement of Kerosene in petroleum reservoir as shown in Fig11. However, the parameters, properties and condition of the petroleum reservoir are the same, which are mentioned in section 4.1.

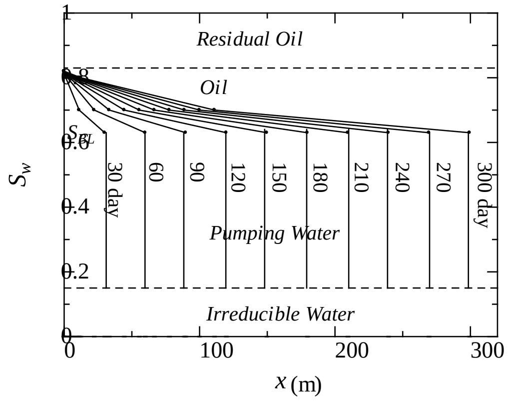


Fig.11 Displacement results of Kerosene

But the fractional flow, average saturation ($\bar{S}_w$ = 0.70) and frontal flow saturation of Kerosene are obtained differently. Therefore, more Kerosene is displaced by waterflooding technique during the same period of time.

The Kerosene recovery factor is calculated from (25) and found to be $RF = 0.6428$, from which the total amount of oil produced up to the breakthrough is $A\ \varphi\ B \times RF$ = 24992.06 m^3 (156950.16 barrels) for the given reservoir.

5. CONCLUSION

The relative permeability and fractional flow value are controlled by rock types and properties, and its appropriate description helps engineers to make confident predictions from the waterflooding calculation. From recovery factor equation (25), it is clearly shown that the oil recovery is belong to average saturation of water and another aspect, the average saturation is the function of the fractional flow of water. As a result, if the average saturation is high, more oil should be recovered from petroleum reservoir and vice versa.

To compare the fractional flow of both oils (heavy oil and Kerosene oil) Fig 7 and Fig 9, it is found out that, the average saturation of water in Kerosene experiment is greater than the average saturation of water in heavy oil experiment. Therefore, the recovery of Kerosene is greater than heavy oil. Which are calculated for heavy oil, that the total amount of oil produced up to the breakthrough is $A\ \varphi\ B \times RF$ = 15901.92 m^3 (= 99864.05 barrels) and for Kerosene is $A\ \varphi\ B \times RF$ = 24992.06 m^3 (156950.16 barrels). Additionally, the front flow of heavy oil is approximately spread to 80 m, and the front flow of light oil is approximately spread to 300 m.

6. ACKNOWLEDGEMENTS

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7. NOMENCLATURE

k	Absolute permeability
k_{rw}	Relative permeability of water
k_{ro}	Relative permeability of oil
k_{ew}	Effective permeability of water
k_{eo}	Effective permeability of oil
k_{rws}	Endpoint relative permeability
μ_w	Water viscosity
μ_o	Oil viscosity
ρ_o	Oil density
ρ_w	Water density
ρ_s	Sand density
p_o	Oil pressure
p_w	Water pressure
q_T	Total amount of oil and water
q_o	Amount of oil
q_w	Amount of water
S_w	Water saturation
S_o	Oil saturation
$\bar{S}_w$	Average water saturation
S_e	Effective saturation
S_{wi}	Irreducible water saturation
S_{ro}	Residual oil saturation
ϕ	Porosity of reservoir
V_p	Pore volume
A	Cross section area
B	Thickness
RF	Recovery factor
f_w	Fractional water flow

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