Oil Displacement by Water in Hauterivian Sandstone Reservoir of Kashkari Oil Field

A. J. Nazari, S. Honma

***Abstract*—**This paper evaluates oil displacement by water in Hauterivian sandstone reservoir of Kashkari oil field in North of Afghanistan. The core samples of this oil field were taken out from well No-21st, and the relative permeability and fractional flow are analyzed. Steady state flow laboratory experiments are performed to empirically obtain the fractional flow curves and relative permeability in different water saturation ratio. The relative permeability represents the simultaneous flow behavior in the reservoir. The fractional flow approach describes the individual phases as fractional of the total flow. The fractional flow curve interprets oil displacement by water, and from the tangent of fractional flow curve can find out the average saturation behind the water front flow saturation. Therefore, relative permeability and fractional flow curves are suitable for describing the displacement of oil by water in a petroleum reservoir. The effects of irreducible water saturation, residual oil saturation on the displaceable amount of oil are investigated through Buckley-Leveret analysis.

***Keywords*—**Fractional flow, oil displacement, relative permeability, simultaneously flow.

I. Introduction

THIS paper focuses on laboratory experimental investigations and analysis of physical properties (permeability and relative permeability) of Hauterivian sandstone reservoir of Kashkari oil field. Furthermore, the collected cores are examined by a specific steady state laboratory experiments, and we interpret the data which are obtained from these experiments. Permeability is basically the measurement of the capacity of the reservoir to transmit fluid and it is a dynamic property. The permeability of petroleum reservoir rock is one of the most influential parameters for determining the production capabilities of a hydrocarbon accumulation. Hence, it can be characterized only by conduction flow experiments with the core samples. The falling head experiment is performed to determine the permeability of Kashkari sandstone reservoir.

In Kashkari oil field, two immiscible fluids (oil and water) are accumulated, and simultaneous flow of oil and water has been occurred in Hauterivian sandstone reservoir. The presence of more than one fluid phase in a reservoir obviously brings in their individual saturations, and their relationships are considered with effective permeability. The measurement of effective permeability and relative permeability of both phases are necessary. Therefore, it is necessary to focus on the relative permeability of oil and water in Hauterivian sandstone reservoir of Kashkari oil field. The relative permeability is measured in different water saturation points by steady state method [1], [2].

The structural map of Hauterivian reservoir of Kashkari oil is illustrated in Fig. 1. The structural map illustrates the steep edges of the oil field. It is a Brachia anticline, the length is 6.83 km, and the width is 1.13 km, and thickness of Hauterivian reservoir varies from 90 m to 126 m. Many wells are drilled in this field. According to the data of these wells, the oil-water contact and the steepness of the edges are found out. Lithology data indicate that the reservoir is made of sandstone with medium permeability, and initial oil reserve is 19.26 billion ton. The most important parameter related to the behavior of both phases is the relative permeability of oil and water, which controls the displacement process of oil by water.

The main dynamism to push oil and to increase pressure in the reservoir is the contact water pushing force, which is illustrated in Fig. 2. The cross-section of the oil field is taken according to the line of A-B. The section is crossed from well No.5, No.8, No.3, No.4, and No.10.

The cross-section of the reservoir shows the location of investigation where natural oil and water contacts. The profile of cross section and depth of the wells is illustrated in Fig. 3. On the line A-B in Fig. 2, the cross-section of this oil field is taken. The cross-section is taken from wells No.5 to No.8. The oil and water contact is selected by the initial information of the well data, and the oil-water contact level is illustrated in Fig. 3.

II. Core Samples

The core samples are obtained from Kashkari oil field which is located in Amu-Darya basin in the north of Afghanistan. The oil field has four different oil reservoirs; Albian, upper Aptian, lower Aptian, and Hauterivian. These are placed vertically in different depths. The core samples were cut out from Hauterivian sandstone reservoir at new well No. 21 which was drilled by CNPCI (China National Petroleum Corporation International) Company in 2012. The whole core sample is illustrated in Fig. 4.

A core plug sample was taken which is a smaller portion or subsample of the whole core sample. Generally, core plugs are cut from whole core samples in two different orientations: perpendicular or parallel to the axis of the whole core. To perform the experiments, the core plugs are cut perpendicularly to the axis of the whole core in the size of 3 cm diameter and 5 cm in length, which is the same size of apparatus. The core plug sample is shown in Fig. 5.

The core plugs after cutting are fixed into the steady state

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laboratory apparatus. The next section provides the details of empirical investigations which are carried out in this study; the experimental apparatus and the interpretations of core samples results of the test for Hauterivian sandstone reservoir of Kashkari oil field will be described for each type of experiments.

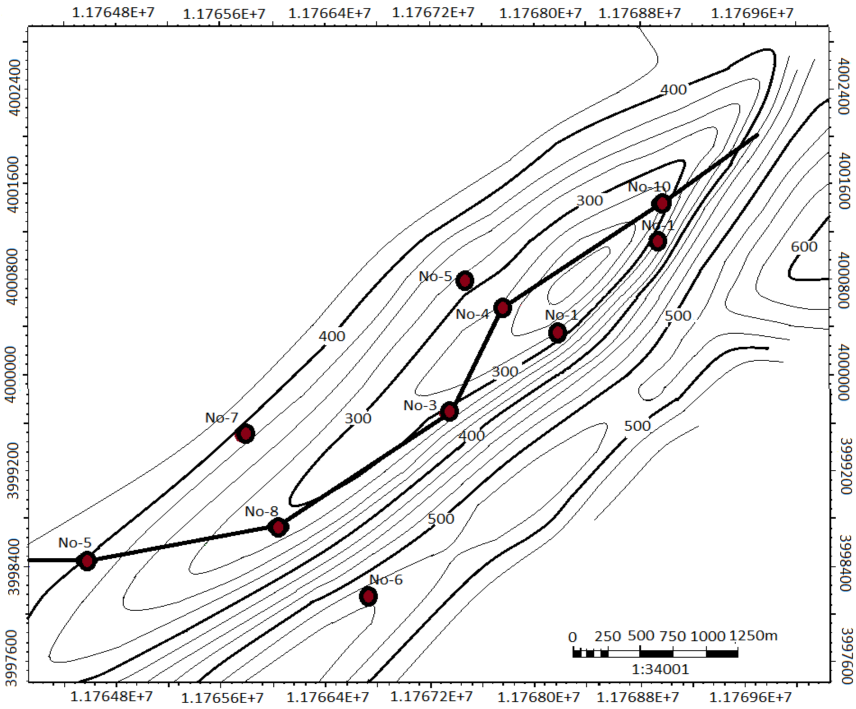

Fig. 1 Structural map of Hauterivian sandstone reservoir of Kashkari oil field [3]

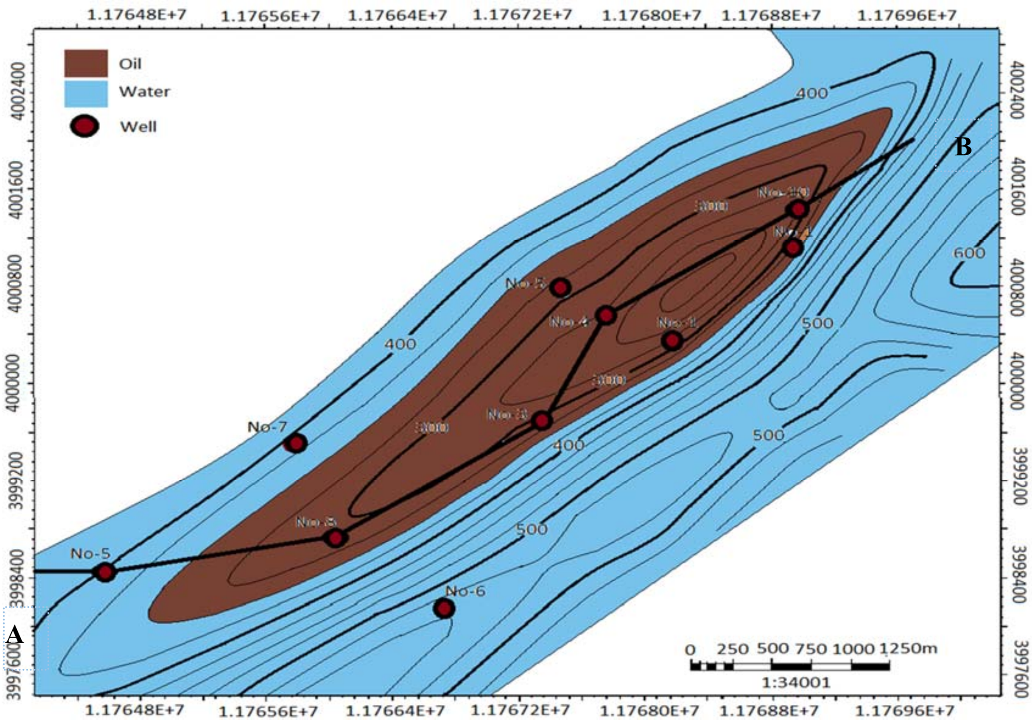

Fig. 2 Oil-water contacts of Hauterivian sandstone reservoir of Kashkari oil field

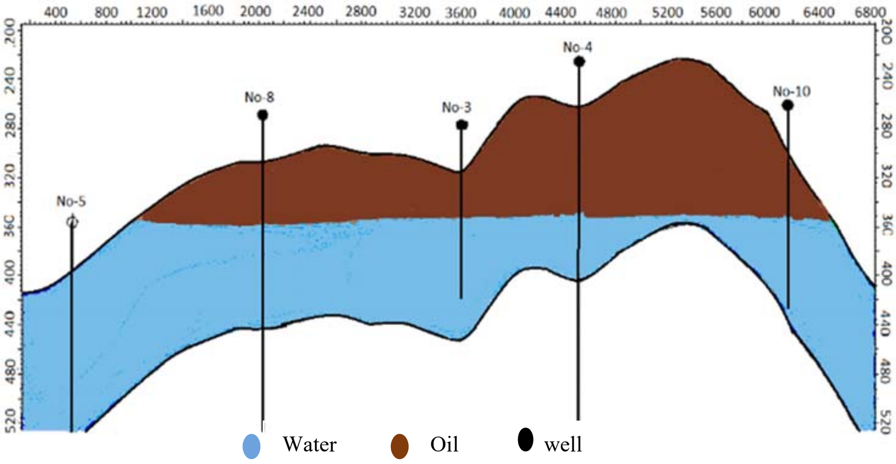

Fig. 3 Cross section of Hauterivian sandstone reservoir of Kashkari oil field

Fig. 4 Whole sample of Hauterivian sandstone reservoir Kashkari oil field

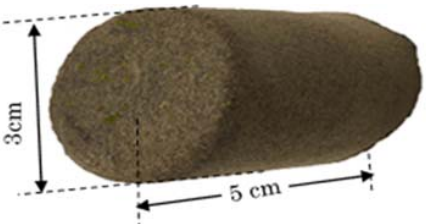

Fig. 5 Core plug sample of Hauterivian sandstone reservoir of Kashkari oil field

III. Laboratory Experiments

A. Steady State Method

The measurement of the relative permeability of oil and water by steady state method was reported in 1942 by Buckley and Leverett [6]. In the steady state method, the total flow rate of oil and water is usually kept constant, while their ratio is changed at the inlet end of the core. It is necessary to wait until the steady state (equilibrium) flow is achieved during the test. In these tests, it is possible to determine the effective permeability for each phase at a given saturation. During the empirical procedure of the experiments, two immiscible fluids (oil and water) are injected simultaneously into the core at constant rates and pressures. When pressure drops are measured across the core, the rates of both phases remain relatively constant, at which the system is assumed to be steady state. The pressure drop and the outlet flow rate of each phase are measured, and the subsequent values are used to calculate the relative permeability of water and oil at that saturation [4].

B. Relative Permeability Experiments

The single fluid phase, that occupies the whole part of the pore space, has the higher permeability than multi-phases, and the interaction between these phases also affects the value of permeability [5].

The laboratory steady state experiments of relative permeability of oil and water are performed for Hauterivian sandstone reservoir samples of Kashkari oil field. The measurement technique for obtaining the two-phase relative permeability data based on the flow experiments is fairly well established on different water saturation. During the experiments, the volume of water, volume of oil, pressure of outlet and inlet, and breakthrough time of the injected fluid are recorded. Next, the quantity of oil and water is calculated. The result of experiments is shown in Table I.

TABLE I
Relative Permeability of Oil and Water

S_w	k_{rw}	k_{ro}	f_w	f'_w
0.23	0.024	0.764	0.074	----
0.31	0.049	0.559	0.176	1.757
0.35	0.086	0.471	0.308	1.546
0.42	0.121	0.396	0.425	1.149
0.49	0.140	0.265	0.561	1.131
0.55	0.186	0.260	0.630	1.000
0.62	0.349	0.165	0.836	1.176
0.71	0.426	0.105	0.906	0.947
0.75	0.598	0.044	0.970	0.012

The relative permeability curves of oil and water in Kashkari sandstone reservoir are illustrated in Fig. 5.

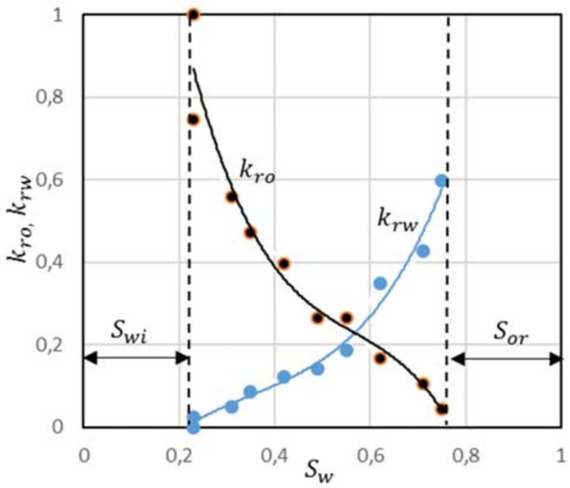

Fig. 6 Relative permeability of oil and water

The points are the exact value of the relative permeability of oil and water, and the curves illustrate the average relative permeability of oil and water during the different water saturation. The water cannot push the oil very well, and a huge amount of oil is remaining in the reservoir.

The wettability characteristics, wetting, and non-wetting phases belong to their distribution in the reservoir. The wetting phase intensively occupies the smallest pore and coats the grains of rock when it penetrates to the reservoir. Therefore, the wetting phase is not flowing at lower saturation.

Since the non-wetting phase occupies the large and central pore. Therefore, the non-wetting phase can flow easily into the reservoir.

According to the experiments of relative permeability of Hauterivian sandstone reservoir of Kashkari oil field, the wetting phase is water, and non-wetting phase is oil, which is illustrated in Fig. 6. Also, the relative permeability curves can be expressed herein by the following cubic approximation functions with respect to effective water saturation for convenience [6].

$$k_{rw} = k_{ews} S_e^3 \tag{1}$$

Approximation relative permeability of oil is obtained,

$$k_{ro} = (1 - S_e)^3 \tag{2}$$

The effective (normalized) saturation is given by,

$$S_e = \frac{S_w - S_{wi}}{1 - S_{wi} - S_{or}} \tag{3}$$

The effective saturation is calculated by (3), where the irreducible water saturation $S_{wi} = 0.22$ and residual oil saturation $S_{or} = 0.25$ which are obtained from experiments. According to effective saturation, the relative permeability of oil and water are calculated by (1) and (2). The data are shown in Table II.

TABLE II
APPROXIMATION RELATIVE PERMEABILITY OF OIL AND WATER

S_w	S_e	k_{rw}	k_{ro}
0.23	0.018	0.000	0.945
0.31	0.166	0.000	0.578
0.35	0.240	0.001	0.437
0.42	0.370	0.006	0.249
0.49	0.500	0.017	0.125
0.55	0.611	0.042	0.058
0.62	0.740	0.141	0.017
0.71	0.907	0.318	0.000
0.75	0.981	0.565	0.000

The cubic approximation of the relative permeability of oil and water with their effective saturation is illustrated in Fig. 7.

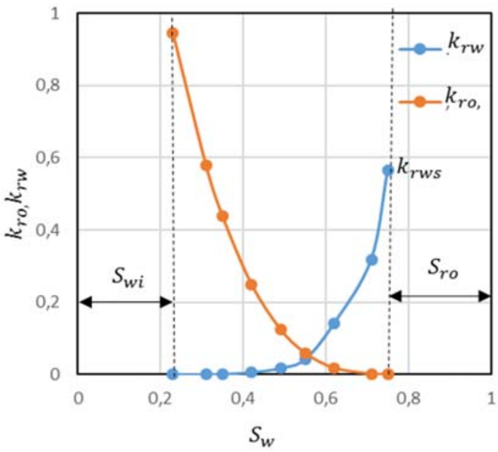

Fig. 7 Relative permeability of oil and water

IV. FRACTIONAL FLOW

The fractional flow of each phase is the ratio of the rate of flow of a phase to the total rate of flow as shown in (4). Hence, the fractional flow of water is the function of water saturation, and the water saturation is increasing from irreducible water saturation to residual oil saturation. Therefore, the value of the fractional flow of water is extending from zero to one, $0 \le f_w \le 1$. Characteristically, the fractional flow curve is S shape, which is illustrated in Fig. 8.

$$f_w = \frac{q_w}{q_T} \tag{4}$$

The fractional flow rate for one-dimensional oil-water system is given by

$$f_w = \frac{1}{1 + \dfrac{k_{ro}}{k_{rw}} \dfrac{\mu_w}{\mu_o}} \tag{5}$$

In the laboratory experiments, the pressure at both ends (the outlet pressure and inlet pressure) and the fractional flow at the outlet, as well as the breakthrough time of the injected fluid, are recorded (the relative permeabilities of oil and water is a function of saturation).

Using the relative permeability of oil and water, the fractional flow of water can be found out based on fractional flow theory, and the fractional flow curve of water is illustrated in Fig. 8.

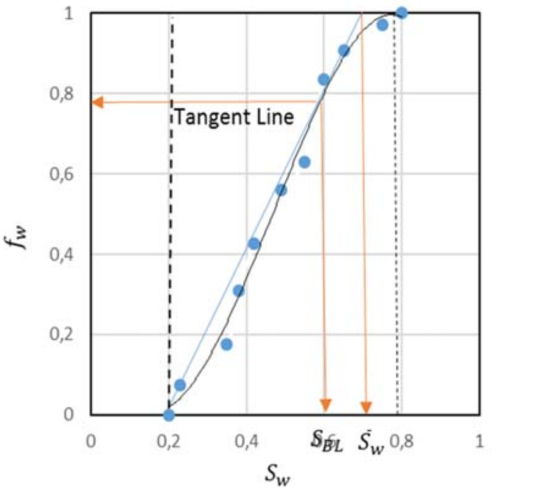

Fig. 8 Fractional flow

The data points in Fig. 8 are the water data of fractional flow for different water saturation, which are empirically obtained in the laboratory. The solid smooth curve illustrates the average value of the fractional flow points.

In this particular experiment of Kashkari oil field of sandstone reservoir, the fractional flow curve is obtained. From the extended point of the tangent line to the curve, the average saturation $\bar{S}_w = 70\%$ and the Buckley-Leveret saturation $S_{BL} = 0.59\,\%$ are found out.

V. Oil Displacement by Water

Buckley and Leverett [6] established the basic equation for describing the immiscible displacement fluid through a porous medium in one dimension in 1942. The fundamental principle for water displacing oil, the velocity is determined through a linear system with a constant water saturation. The Buckley-Leverett solution involves the following assumptions; for two incompressible and immiscible fluids flow in a one-dimension, mass does not transfer between fluids, and permeability and porosity are constant [6], [7].

The Buckley-Leverett displacement equation is given by

$$x_f = \frac{q_t}{A\phi}\left(\frac{df_w}{dS_w}\right)_f \tag{6}$$

which is often called the frontal advance equation.

Based on the theory, the oil displacement by water is empirically considered at Hauterivian sandstone reservoir cores. The displacement of oil by water is illustrated in Fig. 9.

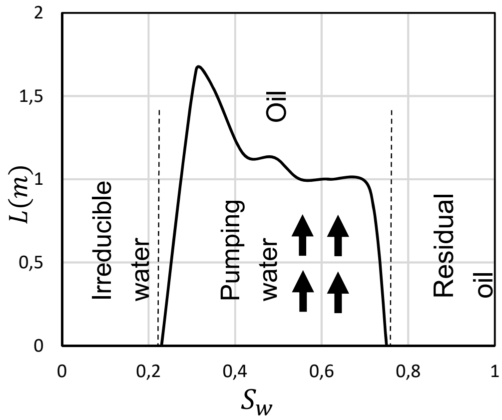

Fig. 9 Displacement curve of oil by water in Hauterivian sandstone reservoir

Fig. 9 illustrates oil displacement by water in core samples of Hauterivian sandstone reservoir. The shape of the water front is somewhat irregular. Hereby, the average displacement curve is obtained and illustrated in Fig. 10, which is absolutely matching to the displacement theory.

Generally, four saturation areas can be classified in Fig. 10. The first area is irreducible water, which is obtained. The second area is the pumping water, which is shown between irreducible water and residual oil saturation. The third area is the residual oil saturation. The fourth area is the oil, which is not displaced by water and it is shown at the top of cover between irreducible water and residual oil. Furthermore, there are other two areas A and B in Fig 10. Both areas are equal to each other. Finally, the abrupt water front can be determined as shown in Fig. 11.

The displacement oil by water is clearly shown in Fig. 11. Based on the Buckley-Leverett concept, the oil displacement by water in Hauterivian reservoir is calculated during one year. The displacement water front is drawn after every 30 days, which is illustrated in Fig. 12.

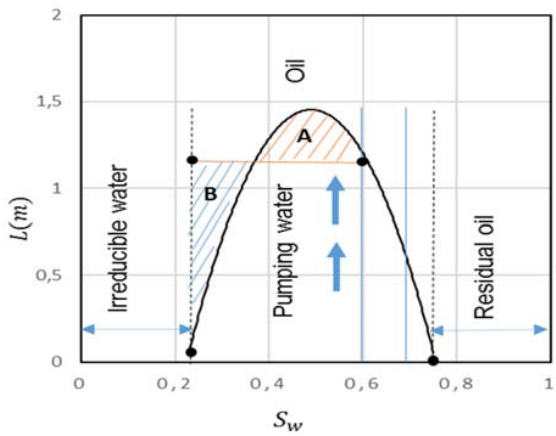

Fig. 10 The average displacement curve of oil by water

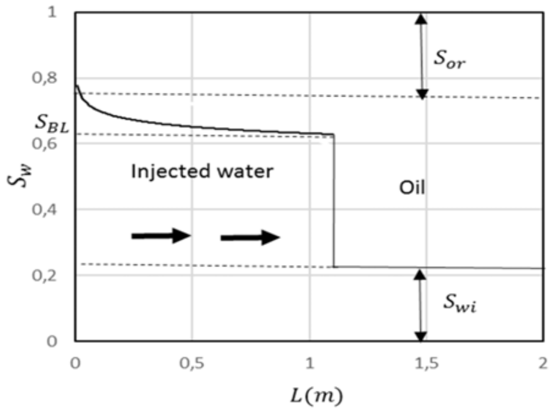

Fig. 11 Displacement curve of oil by water

As a quantitative demonstration for the Buckley-Leverett analysis, a Hauterivian reservoir of the cross-sectional area $A = 113000\, m^2$, thickness $B = 100\, m$, porosity $\varphi = 0.21$ is considered. The relative permeability data which are shown in Table I and Table II are applied here, and viscosity of water and oil are $\mu_w = 0.001\, Pa \cdot s$ and $\mu_o = 0.00242\, Pa \cdot s$, respectively. The total amount of water injected is $q_T = q_w = 2000\, m^3/day$. The water saturation at the front and the average saturation behind the front are found through the graphic method to be $S_{BL} = 0.59$ and $\bar{S}_w = 0.70$.

Fig. 12 illustrates the displacement calculation results by Buckley-Leverett analysis. It is seen from the curves of displacement, that the front flow water saturation is distributed with a constant speed during the breakthrough time at $t = 360$ days.

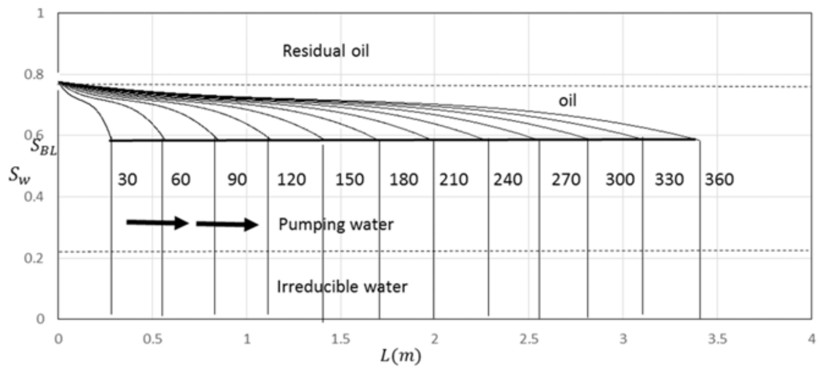

Fig. 12 Displacement of oil by water

The average saturation $\bar{S}_w$ behind the Buckley-Leverett saturation is obtained by [8].

$$\overline{S}_w = S_{wi} + \frac{1}{\left(df_w/dS_w\right)_{BL}} \tag{7}$$

The oil recovery factor is calculated from

$$RF = \frac{\overline{S}_w - S_{wi}}{1 - S_{wi}} \tag{8}$$

and found to be $RF = 0.6153$, from which the total amount of oil produced up to the breakthrough is $A\, \varphi\, B \times RF = 1432295.3\, m^3$ ($= 9008866.04\, barrels$) the Hauterivian reservoir.

VI. Conclusion

The result reveals that the injection water can displace the oil toward upward. The residual oil and irreducible water exactly find out from relative permeability experiments, the outcome displays that too much oil is remaining in the reservoir. The average saturation and the Buckley-Leverett saturation are graphically obtained from fractional flow curve.

The effects and behavior of relative permeability of oil and water are shown in Figs. 6 and 7. The water is a wetting phase, and oil is a non-wetting phase. The calculation result of water-flooding technique under the same reservoir condition with the Buckley-Leverett analysis is shown in Fig. 9. We can obtain the saturation profile and can provide useful information for applying the water-flooding technique in petroleum reservoir. Finally, the curves in Fig. 12 illustrate the displacement of oil by water in Hauterivian sandstone for every 30 days.

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