New Understanding of the Retention Mechanism of "Residual Oil in the Form of Oil Droplets (or Oil Column)"

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Abstract. Based on the oil-water two-phase liquid flow model, with equal-viscosity and water-wet unequal-diameter parallel channels, the previous researches on the retention mechanism of "residual oil in the form of oil droplets or oil column" during water flooding, and they stated that "residual oil in the form of oil droplets (or oil column)" can be retained in both large and small channels. Re-examination of the model shows that "residual oil in the form of oil droplets (or oil column)" cannot be retained in large channels, but only in small channels. By changing the wettability and oil-water viscosity (variable viscosity) of this model, the small channel retention characteristics of "residual oil in the form of oil droplets (or oil column)" remain unchanged. This research shows that: (1) When the oil-water phase flows in the unequal-diameter parallel channel model, the flow velocity of the large channel is always greater than the small channel, and the "residual oil in the form of oil droplets (or oil column)" is always retained in the small channel. (2) The retention of small channels of "residual oil in the form of oil droplets (or oil column)" is general, and is not affected by changes in factors such as pressure difference, capillary force, total flow, wettability, and oil-water viscosity ratio.

1. Introduction
The parallel channel model with unequal-diameter is one of the most simplified models in rock pore networks [1]. Since Dawe et al. proposed a parallel channel model with unequal-diameter in 1978, this model has been widely used in the study of the microscopic mechanism of residual oil retention [2-12]. The previous works studied the retention mechanism of "residual oil in the form of oil droplets (or oil column)" during water flooding based on the oil-water two-phase liquid flow model with equal-viscosity and water-wet unequal-diameter parallel channels. "Residual oil" can be retained in both large and small channels [1-3]. However, re-examination of the model shows that "residual oil in the form of oil droplets (or oil column)" cannot be retained in large channels, but only in small channels. After further changing the model's wettability and oil-water viscosity (unequal viscosity), it was found that the small channel retention characteristics of "residual oil in the form of oil droplets (or oil column)" remain unchanged. The research shows that the oil-water two-phase flow in the unequal-diameter parallel channel model always remains as residual oil in small channels. This phenomenon is general and is not affected by
changes in factors such as pressure difference, capillary force, total flow, wettability, and oil-water viscosity ratio.

2. Previous understanding of the retention mechanism of "residual oil in the form of oil droplets (or oil column)"

In the rock pore network, large and small channels are staggered with each other, whether in series or in parallel. It is a basic unit that is often presented in the Figure 1, and it is also the most simplified model in a rock pore network. It is assumed in the Figure 1 that the radius of the large capillary channel is $r_1$, the flow rate is $q_1$, the radius of the small capillary channel is $r_2$, and the flow rate is $q_2$. The two capillary channels have the same length, both are L, and both are hydrophilic. The viscosity of oil and water in each channel is the same ($\mu_1 = \mu_2 = \mu$).

\[ \Delta p_1 = \frac{8q_1\mu L}{\pi r_1^4} \]  
\[ p_{c1} = \frac{2\sigma \cos \theta}{r_1} \]  
\[ \Delta p_2 = \frac{8q_2\mu L}{\pi r_2^4} \]  
\[ p_{c2} = \frac{2\sigma \cos \theta}{r_2} \]

Where $\Delta p_1$ and $\Delta p_2$ represent the pressure drops caused by the viscous resistance in the large and small channels, $p_{c1}$ and $p_{c2}$ represent capillary forces in large and small channels, respectively.

The two capillary channels are connected in parallel, and the pressures at the two points of A and B are equal, so the pressure difference $\Delta p = p_A - p_B$ is also the same, in addition, the pressure balance relationship in each channel is calculated as following,
\[ \Delta p = -p_1 + \Delta p_1 = -p_2 + \Delta p_2 \]  

(5)

According to the above equations, and \( q = q_1 + q_2 \), \( q_1 \) and \( q_2 \) are calculated as following,

\[ q_1 = \frac{4\mu Lq}{\pi r_2^4} - \left( \frac{1}{r_2} - \frac{1}{r_1} \right) \sigma \cos \theta \left( \frac{1}{r_1} + \frac{1}{r_2} \right) \]  

(6)

\[ q_2 = \frac{4\mu Lq}{\pi r_1^4} - \left( \frac{1}{r_2} - \frac{1}{r_1} \right) \sigma \cos \theta \left( \frac{1}{r_1} + \frac{1}{r_2} \right) \]  

(7)

Where \( \sigma \) represents the oil-water interfacial tension, \( \theta \) represents wetting angle.

In addition, according to \( \frac{q_1}{q} = v_1 \pi r_1^2 \) and \( \frac{q_2}{q} = v_2 \pi r_2^2 \), flow velocity ratio between two capillary channels is calculated as following,

\[ \frac{v_1}{v_2} = \frac{\frac{4\mu Lq}{\pi r_2^4} - \left( \frac{1}{r_2} - \frac{1}{r_1} \right) \sigma \cos \theta}{\frac{4\mu Lq}{\pi r_1^4} + \left( \frac{1}{r_2} - \frac{1}{r_1} \right) \sigma \cos \theta} \]  

(8)

Where \( v_1 \) and \( v_2 \) represent moving speed of oil-water interface in large and small channels respectively.

When the two-phase interface reaches the outlet end B at the same time, that is \( v_1 = v_2 \), which is the most ideal oil-displacement situation. At this time, the total flow \( q_e \) of the parallel channels is calculated as following,

\[ q_e = \pi \sigma \cos \theta \left( \frac{r_2^3}{r_1} + \frac{r_1^3}{r_2} \right) \frac{r_1 r_2}{4\mu L (r_1 + r_2)} \]  

(9)

From the equations (8)-(9), the following conclusions can be drawn: ①When \( q = q_e \), the velocities in the large and small channels are equal \((v_1 / v_2 = 1)\), and the oil-water interface reaches the outlet at the same time, leaving no residual oil. ②When \( q < q_e \), the capillary force plays a major role, so the velocity in the small channel is higher \((v_1 / v_2 < 1)\), the oil-water interface reached the outlet end firstly, and residual oil remained in the large channel. ③When \( q > q_e \), because the pressure difference plays a major role, the velocity in the large channel is higher \((v_1 / v_2 > 1)\), the oil-water interface reaches the outlet end firstly, and residual oil remains in the small channel. ④The above analysis shows that the flow velocity in the channel is not always \( v_1 > v_2 \), and that is determined by the pressure difference \( \Delta p \) and capillary force \( p_c \).

3. New understanding of the retention mechanism of "residual oil in the form of oil droplets (or oil column)"

The above model is still used in this paper, and the flow rate and velocity of water driving oil in capillary channels are calculated as following,

\[ q_i = \frac{\pi r_i^3 \Delta p}{8\mu L} \]  

(10)

\[ v_i = \frac{r_i^2 \Delta p}{8\mu L} \]  

(11)
\[ q_2 = \frac{\pi r_2^2 \Delta p_2}{8 \mu L} \]  \hspace{1cm} (12)

\[ v_2 = \frac{r_2^2 \Delta p_2}{8 \mu L} \]  \hspace{1cm} (13)

Considering the equations (2), (4), (5), (12), and (13), the ratio of the flow velocity in the two capillary channels can be calculated as following,

\[ \frac{v_1}{v_2} = \frac{r_1^2 (\Delta p + P_r)}{r_2^2 (\Delta p + P_{r2})} = \frac{r_1^2 \Delta p + 2r_1 \sigma \cos \theta}{r_2^2 \Delta p + 2r_2 \sigma \cos \theta} \]  \hspace{1cm} (14)

It can be proved that equations (14) and (8) are equivalent.

According to the assumptions of the model, we can know that \( r_1 > r_2, \Delta p \geq 0, 2 \sigma \cos \theta > 0 \) (water wet, capillary force is the driving force \( \theta < 90^\circ \)), \( r_2^2 \Delta p \geq 2r_1 \sigma \Delta p \), \( 2r_1 \sigma \cos \theta > 2r_2 \sigma \cos \theta \). Therefore, \( v_1 / v_2 > 1 \) always holds.

To sum up, the following conclusions can be drawn: ① For oil-water two-phase liquid flow model with equal-viscosity and water-wet unequal-diameter parallel channels, there is no way to make the flow velocity in the large and small channels equal and the oil-water interface reach the outlet end at the same time without leaving residual oil. There is no total flow \( q_o \), so that equation (9) holds. Therefore, equation (9) is a pseudo-proposition. ② No matter how the pressure difference \( \Delta p \), capillary force \( \sigma \), and total flow rate \( q \) change, the flow velocity of the large channel is always greater than the flow velocity of the small channel \( (v_1 / v_2 > 1) \), and the oil-water interface in the large channel always reaches the outlet end firstly, thereby retaining "oil droplets" in the small channel.

4. Retention of "droplet (or oil column) residual oil" in the small channel is general

4.1. Oil-water two-phase liquid flow model with equal-viscosity and oil-wet unequal-diameter parallel channels

Is the above conclusion based on retention of "residual oil in the form of oil droplets (or oil column)" in the small channel for water-wet suitable for the oil-wet model? The oil-water two-phase liquid flow model with equal-viscosity and oil-wet unequal-diameter parallel channels is used as an example for analysis.

For the equal-viscosity oil-wet model, the ratio of the flow velocity in the two capillary channels is calculated as following,

\[ \frac{v_1}{v_2} = \frac{r_1^2 (\Delta p + P_r)}{r_2^2 (\Delta p + P_{r2})} = \frac{r_1^2 \Delta p + 2r_1 \sigma \cos \theta / r_1}{r_2^2 \Delta p + 2r_2 \sigma \cos \theta / r_2} \]  \hspace{1cm} (15)

According to the assumptions of the model and considering the simultaneous flow of liquid in the two channels, then \( r_1 > r_2, \Delta p > |P_r| > |P_{r2}| > 0, 2 \sigma \cos \theta < 0 \), (oil-wet, capillary force is resistance \( \theta > 90^\circ \)), so we can know \( r_1^2 / r_2^2 > 1, (\Delta p + 2 \sigma \cos \theta / r_1) > 1 \). Therefore, \( v_1 / v_2 > 1 \) always holds.

To sum up, the following conclusions can be drawn: ① For oil-water two-phase liquid flow model, with equal-viscosity and oil-wet unequal-diameter parallel channels, regardless of how the pressure difference \( \Delta p \), capillary force \( \sigma \), and total flow rate \( q \) change, as in the equal-viscosity water-wet model, the flow velocity of the large channel is always greater than the flow velocity of the small channel \( (v_1 / v_2 > 1) \), and the oil-water interface in the large channel always reaches the outlet end firstly, thereby retaining "oil droplets" in the small channel. ② This shows that the property of "residual oil in the form of oil droplets (or oil column)" retention in small channels is not related to the model wettability. That
is to say, for oil-water two-phase liquid flow model, with equal-viscosity unequal-diameter parallel channels, retention of "residual oil in the form of oil droplets (or oil column)" in the small channel is general.

4.2. Oil-water two-phase liquid flow model with unequal-viscosity unequal-diameter parallel channels

Is the conclusion of retention of "residual oil in the form of oil droplets (or oil column)" in the small channel suitable for unequal-viscosity models? If we consider the unequal viscosity of oil and water, is the above conclusion correct? Here, oil-water two-phase liquid flow model, with unequal-viscosity unequal-diameter parallel channels, is used as an example for analysis.

First, an oil-water two-phase flow model with a single capillary channel (Figure 2) is used as an example for discussion. The two fluids with viscosity $\mu_1$ (water) and $\mu_2$ (oil) flow viscously under the pressure difference $\Delta p$ and capillary force $p_c$ in a capillary channel radius of which is $r$. Then, the flow velocity of oil-water interface is calculated as following,

$$v_x = \frac{r^2(\Delta p + p_c)}{8[\mu_1 x + \mu_2 (L-x)]} \quad (16)$$

The equation (16) shows that the flow velocity of the oil-water two-phase liquid flow of unequal viscosity in a single capillary channel varies and can be regarded as a function of $x$. When $\mu_1 < \mu_2$, as $x$ increases, the flow velocity will gradually become faster; conversely, when $\mu_1 > \mu_2$ and $x$ increases, the flow velocity will become slower.

Compared with Figure 1, it can be seen that if large and small capillary channels of equal length have a common inlet A and a common outlet B, then in the oil-water two-phase liquid flow model with unequal-viscosity unequal-diameter parallel channels, the velocity ratio of the oil-water interface of the large and small channels at position $x$ is calculated as following,

$$\frac{v_{x-1}}{v_{x-z}} = \frac{r_1^2(\Delta p + p_{c1})}{r_2^2(\Delta p + p_{c2})} \quad (17)$$

It can be seen that the form of (17) is consistent with the forms of (14)-(15). From the above discussion, it can be known that when the position of the oil-water interface in the large and small capillary channels is the same, the velocity in the large channel is always greater than the velocity of the small channel ($v_{x-1}/v_{x-z} > 1$). However, during the actual seepage process, the positions of the oil-water interface in the large and small channels are different. Considering the situation of (17), it is clear that the oil-water interface in the large channels must reach the outlet earlier. That is, whether the oil-water viscosity is equal does not affect the characteristics of the "residual oil in the form of oil droplets (or oil column)" retained in the small channel. In summary, for oil-water two-phase liquid flow model, with unequal-diameter parallel channels, there is always residual oil remaining in the small channels.

5. Conclusion

When two phases of oil and water flow in the unequal-diameter parallel channel model, the flow velocity in the large channel is always greater than the velocity in the small channel, and the "residual oil in the form of oil droplets (or oil column)" is always retained in the small channel. The retention of "residual
oil in the form of oil droplets (or oil column)" in the small channel is general and has nothing to do with factors such as pressure difference, capillary force, total flow, wettability, and oil-water viscosity ratio.

Acknowledgments
This work was financially supported by the National Science and Technology Major Project "Effective Development Technology for Extra Low Permeability Reservoirs" of China (Grants No. 2011ZX05013-006).

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