# Research and Application of Multi-slug and Equi-fluidity Oil Displacement Mechanism

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**Abstract.** In this paper, several aspects of the improvement of the oil recovery were analyzed theoretically based on the mechanism that equi-fluidity enhances the pressure gradient. These aspects include the increase of the flow rate and the recovery rate, of the swept volume, and of the oil displacement efficiency. Also, based on the actual situation, the author designed the oil displacement method with gathered energy equi-fluidity, realizing the expectation of enhancing oil recovery with multi-slug and equi-fluidity oil displacement method.

**Keywords:** Multi-slug, Equi-fluidity, energy-gathered, confluence.

## 1. Introduction

Multi-slug and equi-fluidity oil displacement with binary flooding uses the oil-displacing agent for big pore canals with a high permeability in the strata to reduce the energy loss caused by the transportation of oil displacing agent, effectively displacing the low permeability layer with energy; based on the mechanism that slugs of different viscosity matches the strata of different permeability, the slug of high viscosity is first injected into the deep part of high permeability layer, and then the slug of secondary viscosity is injected and it flows into the secondary permeability layer or region driven by the differential pressure between the slugs forming at the time when slug of secondary viscosity encounters the slug of high viscosity; In the same way, all slugs are injected in turn, forming a stereoscopic slug wall in the deep strata, so that the overall load pressure turns into a partial one and the energy is gathered at the moving slug [1]. In this case, the local pressure gradient is enhanced, and the injected water is forced to flow into the smaller pores, forming a relatively complete piston-like oil displacement. Under the condition of equi-fluidity, each slug of different permeability layers can approximately achieve the parallel movement, expanding the distribution span and the working area of slugs, and this can enhance the swept volume, control the non-effective displacement; and meanwhile, by increasing the local differential pressure, the remaining oil which has a wider swept area is used, and accordingly the efficiency of oil recovery can be further improved.

## 2. Mechanism of the improvement of pressure gradient with equi-fluidity method

The Enhanced Oil Recovery can be achieved from the following three aspects by increasing the pressure gradient [2].

The flow rate and oil recovery can be increased by the increment of pressure gradient. The differential pressure of the multilayer radius flow is denoted as, pe-pw, and the total flow rate Q can be calculated by the formula as follows:

$$\frac{2\pi kh(p_1-p_2)}{\mu\ln(R_e/R_w)}=\frac{2\pi k_1h_1(p_1-p_2)}{\mu\ln(R_e/R_w)}+\frac{2\pi k_2h_2(p_1-p_2)}{\mu\ln(R_e/R_w)}+\frac{2\pi k_3h_3(p_1-p_2)}{\mu\ln(R_e/R_w)}$$

$R_e$—— external radius

$R_w$—— well radius

$p_e$—— injection pressure

$p_w$—— production pressure

Increasing the pressure gradient can increase the swept volume. Several cases for increasing the swept volume:

a. Increase the swept volume of the plane radial flow of non-mainstream line.

b. Increase the swept volume of vertical heterogeneous layer of low permeability.

c. Increase the swept volume of microscopic parallel pores.

d. Utilize more capillaries with smaller diameter.

It is necessary that $\Delta p$ is no smaller than the capillary force for oil displacement, and it means that in order to make the oil droplets flow in the pores of stratum, the applied pressure must be greater than the capillary force, namely to overcome the capillary resistance [3].

In the cylindrical capillary pores of equal diameter, when liquid balls or bubbles are stationary, they suffered capillary force, $p_1$, as follows:

$$p_1 = \frac{2\sigma}{R} - \frac{\sigma}{r} = \frac{2\sigma}{r}(\cos\theta - 0.5)$$

$p_1$—— capillary force

σ—— surface tension

$\theta$—— wetting angle

$r$—— radius of capillary

From the above equation, it can be observed that the greater the pressure gradient is, the more remaining oil is used.

Increasing the pressure gradient can improve the oil displacement efficiency. When investigating the starting pressure of displacement process under certain permeability, the pore voids are often simplified into parallel capillaries of the same diameter, although they are rarely straight, smooth or equi-diameter cylindrical channels in the strata [4-5].

In a capillary with a length of L and an inner radius of $r_o$, fluid with the viscosity of μ undergoes a laminar flow under the differential pressure of $p1$-$p2$. If the capillary wall can be damped by this fluid, the flow rate is zero at the wall, and is of the maximum at the center of the capillary. This flow can be regarded as a set of concentric fluid cylinders moving at different speeds, and the viscous force existing between the liquid cylinders can be represented by the formula:

$$F = \mu A \frac{dv}{dx}$$

$A$—— circle area of the concentric liquid cylinder

$Dv/dx$—— velocity gradient

$F$—— viscous force

So the viscous force applied on the liquid cylinder with a radius of r is:

$$F_r = \mu A \frac{dv}{dx} = \mu(2\pi r L)\frac{dv}{dr}$$

And the driving force applied on a liquid cylinder is $(p_1\text{-}p_2)\,\pi r^2 \times 10^{-5} N$. Assuming there is no acceleration for the flow, then the driving force and the viscous resistance should be equal:

$$\mu(2\pi r L)\frac{dv}{dr} + (p_1 - p_2)\pi r^2 = 0$$

As a result, integration of them leads to:

$$v = -\frac{(p_1 - p_2)r^2}{4\mu L} + C$$

When $r = r_o$, $v = 0$, its integration constant can be obtained, so:

$$v = \frac{(p_1 - p_2)(r_0^2 - r^2)}{4\mu L}$$

The above formula shows the moving velocity of liquid cylinder with radius of r, and reveals that the figure of the velocity changes in a parabolic style, that is to say, the maximum speed is at the center, while at the wall, it decreases to zero.

The volume flow rate going through the liquid cylinder unit with a thickness of $d_r$ can be calculated as $dq = v \cdot dA$, $dA = 2\pi rdr$, so the flow volume going through capillary is the integration of the flow volume of these liquid cylinder units, namely:

$$q = \int_o^q dq = \int_o^{r_o} v \cdot dA = \int_o^{r_o} \frac{(p_1 - p_2)(r_0^2 - r^2)}{4\mu L} 2\pi rdr$$

After the integration, it can be obtained that:

$$q = \frac{(p_1 - p_2)\pi r_0^4}{8\mu L}$$

$$q = \frac{\Delta p \pi r_0^4}{8\mu L}$$

## 3. Implementation process for energy-gathered equi-fluidity oil displacement method

Implementation process for energy-gathered equal-fluidity oil displacement method includes shunting, energy gathering, and confluence flow accumulation.

### 3.1 Shunting or split-flow of injected agents

a. Inject high-viscosity slug $\mu_h$, and the slug enters the high permeability layer $K_h$ according to the principle of the least flow resistance.

b. Inject secondary high-viscosity slug $\mu_m$, which accesses the secondary permeability layer $K_m$ more easily than the $\mu_h$ does due to the low flow velocity of the high-viscosity slug $\mu_h$.

c. according to the same principle, the subsequent multi-slug $\mu_1$ shunts into the corresponding low-permeability layer $K_l$.

### 3.2 Damming and energy gathering

a. Design the slugs of different viscosity ($\mu_1>\mu_2>\mu_3$) corresponding to different permeability layers ($K_1>K_2>K_3$), so that each slug flow in the corresponding permeable layer has an equal fluidity.

b. Inject multiple slugs according to varied concentrations in descending order, each slug migrates starting from the high-permeability layer, which reduces energy loss during the transportation of the displacing agents, and achieves the energy gathering. Owing to the resistance of high seepage flow and low-velocity slug ahead, subsequent injected agents split into the corresponding permeable layer in turn.

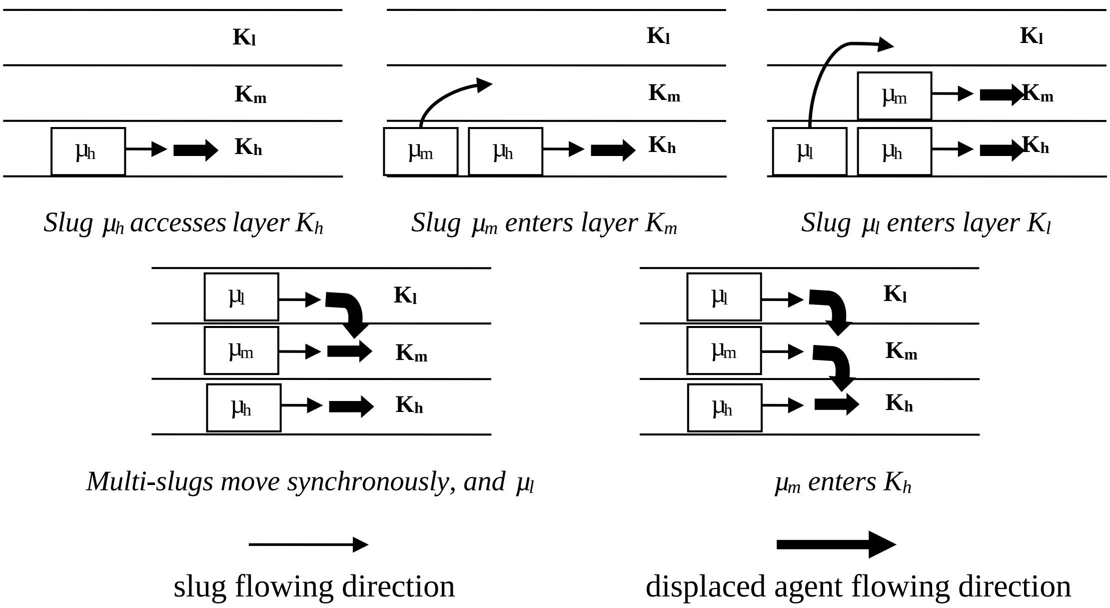


Fig. 1. Illustration of the shunting, energy gathering and confluence.

c. As all fluidity of the cross-section are equal, the flow velocity of slug in each layer are equal and synchronous; since no cross flow exists, the main energy is applied on the movable slug wall, so that the smaller movable plugs can effectively enhance the local pressure gradient, and strengthen the energy gathering effect [6-7].

### 3.3 Confluence of crude oil

a. Many slugs of different viscosity split and access the corresponding permeability layer in turn.

b. The cross-sectional equal-fluidity enables the multi-slug of each layer to flow at the same speed synchronously.

c. The displaced fluid of medium- and low-permeability layers flows into the high-permeability layer of low resistance and low pressure, to achieve the confluence.

## 4. Conclusion

As can be seen from the paper, when the pore size is fixed, the greater the pressure gradient applied on both sides of the pores, the larger the liquid flow going through the pores. The liquid penetration in the imaginary rock follow the same percolation law, so the larger injection pressure is, the greater the swept efficiency of fluid displacement is, thereby improving the oil recovery. Therefore, it can be concluded that increment of the pressure gradient can effectively improve the production rate and oil recovery.

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