Theoretical and Experimental Study on Nonlinear Flow Starting Pressure Gradient in Low Permeability Reservoir

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Abstract. In order to reveal the seepage characteristics of low permeability fluid in reservoir pores, the seepage mathematical equation of low permeability reservoir is derived based on the mechanical equilibrium equation. The characteristics and rules of oil and water seepage flow in low permeability reservoir are studied. The seepage process and starting mechanism are deeply analyzed. The starting pressure gradient is derived from its yield stress and surface force, and the boundary layer intensifies the nonlinear degree of seepage. In the actual reservoir development, the nonlinear characteristics of seepage should be fully grasped. The results show that the starting pressure is related to permeability and other physical properties such as viscosity and porosity.

1. Introduction
With the continuous development and utilization of oil resources, more low permeability oil fields will be put into development. Due to its low permeability, the fine flow channel of oil and gas water, the great seepage resistance, the interaction force between liquid-solid interface and liquid-liquid interface, the seepage mechanism of the low permeability reservoir changes to some extent and deviates from the Darcy's law. These internal factors are reflected in the oil field production, resulting in the following phenomena: (1) the daily output of a single well is small, (2) the steady production condition is poor, (3) the output decreases quickly, (4) the water absorption capacity of the injection well is poor, (5) the water injection pressure is high, (6) and the oil injection well is difficult to see the water injection effect. Because of the above problems, it is very difficult to stabilize oil production of the field[1]. Therefore, how to improve the development effect of the low permeability oil field is an urgent problem waiting to be solved. In this study, based on the experimental data, the mechanism and characteristics of oil-water seepage in low permeability reservoirs are studied.

2. Study on the Complexity of Seepage in Low Permeability Oil Layer
The complexity of low seepage flow is mainly reflected in the following four aspects:
1) Nonlinear characteristics of oil-water seepage
Because of the interface tension between solid phase and liquid phase, there is a boundary layer of crude oil on the inner surface of the pore of oil layer. In the boundary layer, the composition and
properties of crude oil are very different from that of bulk crude oil. There are ordered changes of components, structural viscosity characteristics and yield values. In addition to the properties of crude oil itself, the thickness of the boundary layer is also related to the pore size, driving pressure gradient, etc. Through the study of the Darcy’s law, it can be seen that when the permeability is medium and high, the pore channel of crude oil flow is not too small, and the boundary layer of crude oil is not too thick. As a result, the proportion of crude oil in boundary layer is not too large compared with the total oil volume, and the effect of the non-Newtonian property of the boundary layer crude oil on the law of linear seepage is not obvious. However, this effect can not be ignored for low permeability reservoirs. It will make the seepage law change obviously, and the starting pressure will appear.

2) Change of permeability of porous media

The permeability of porous media is the sum of the permeability of many different pore sizes. For high permeable strata, the pore system is mainly composed of large pore channels. When the thin oil or water flows in it, it is not easy to monitor the starting pressure the influence of the flow rate. Therefore, in the rectangular coordinate system of flow rate and pressure gradient, the flow experiment with high permeability core is presented as a straight line. However, for low permeability and ultra-low permeability strata, the pore system of the low permeability core is basically composed of small pore channels, and each channel has its own starting pressure gradient. When the driving pressure gradient is greater than the starting pressure gradient of the channel, the oil and water in the channel begin to flow, thus increases the permeability value of the whole core. As the driving pressure gradient increases, more channels will be involved in the flow, and the core permeability will be enhanced. Therefore, in the flow experiment of low permeability core, it is a curve and a straight line, rather than a single straight line. It indicates that the permeability increases with the increase of pressure gradient and tends to a fixed value^2^.

3) Variation of cross-sectional area of fluid flow in porous media

The cross-sectional area of fluid seepage is related to the pressure gradient. When the pressure gradient is very small, the fluid flows only along the central part of the larger channel, while the fluid in the smaller channel and the fluid in the middle edge of the larger channel do not flow. We call the fraction of the actual flow to the total fluid as the flow saturation, and the ratio of the volume of the actual flow to the total volume of the core as the flow porosity. Both flow porosity and flow saturation are functions of the pressure gradient and are not a constant value^3^. For medium with high permeability, the flow porosity can reach a stable value quickly with the increase of pressure gradient. However, for low permeability reservoirs, things become much more complicated, and cause certain changes in seepage laws.

4) Starting pressure gradient exists in seepage flow in low permeability rock

Because the pore radius of low permeability reservoir is very small and the proportion of pore channel less than 1μm is very large, the influence of the crude oil boundary layer is significant, and the starting pressure gradient appears during the flow process. A large number of research data show that the starting pressure gradient is inversely proportional to the permeability.

3. Determination of Starting Pressure Gradient in Low Permeability Reservoir

In the porous channels with low permeability, the effect of molecular force on the solid-liquid interface will be significantly enhanced, which will hinder the movement of the fluid. When the driving pressure gradient exceeds a starting pressure gradient, liquid seepage can occur. Not only for crude oil, but also for water, it is characterized by:

1) when the pressure gradient is in the lower range, the increase of seepage velocity is concave nonlinear curve, whereas the seepage velocity increases linearly.

2) the intersection point between the extension of the straight line and the pressure gradient axis (without passing through the coordinate origin) is the starting pressure gradient.

3) the effect of turbulence is not obvious in the experimental range, the seepage characteristics are related to the permeability and fluid properties. The low permeability or large viscosity of the crude oil
will result in the long extension of the concave nonlinear curve section and large the starting pressure gradient.

According to the seepage characteristics expressed by a large number of experimental data, we can use mathematical equations to express the seepage process.

Figure 1 represents the relationship between the mean seepage velocity \( V \) and the \( \Delta P/L \) pressure gradient. A linear law with starting pressure gradient is used to describe the seepage process. The mathematical equations are as follows:

\[
V = 0 \quad (\frac{\Delta P}{L} \leq g)
\]

\[
V = \frac{K}{\mu} \left( \frac{\Delta P}{L} - g \right) \quad (\frac{\Delta P}{L} \geq g)
\]

Where:

- \( K \) — Effective permeability, \( \times 10^{-3} \mu m^2 \);
- \( \mu \) — Fluid viscosity, mPa·s;
- \( \Delta P/L \) — Starting pressure gradient, MPa/m;
- \( L \) — Model length, cm;

The formula reflects the basic characteristics of seepage in low permeability formation and can be used in engineering calculation.

It can be seen from the equations that the starting pressure gradient is affected by reservoir porosity, permeability and fluid ultimate dynamic shear stress. The results show that the greater the viscosity of crude oil is, the greater the thickness of crude oil boundary layer is. In other words, the viscosity of crude oil is proportional to the thickness of crude oil boundary layer\(^4\). It can be inferred that with the increasing viscosity, the limit shear stress will increase, and the viscosity is proportional to the limit shear stress. Therefore, it is assumed that the effect of fluid properties on the starting pressure gradient can affect the viscosity, and the starting pressure is proportional to the viscosity of the fluid.

4. Experimental Verification of Starting Pressure Gradient

In Daqing Oilfield of PetroChina, the experimental data of starting pressure gradient were obtained from 3 ports under different temperature conditions. The results are shown in Table 1, indicating that the starting pressure gradient increases with the decreasing pressure and increasing viscosity. The results of Table 1 verify the analysis in Section 3. The fitting results are shown in Figure 2 and Figure 3.

It can be seen from the figures that Dong161 well and Shu131 well belongs to the same type of reservoir, Jin251 well represents another type of reservoir, and all of them meet the linear relationship; the linear relationship is good and can be treated as follows:

Dong161 well and Shu131: \( \lambda = 0.0127 \mu, \sqrt{\frac{\phi}{K}} \)
**Jin251 well:** \[ \lambda = 0.0524 \mu \sqrt{\frac{\phi}{K}} \]

Table 1. Test Data Table of Starting pressure Gradient of Daqing Changyuan sheet reservoir

| Well name | Permeability (10^{-3}\mu m^2) | Porosity (%) | Viscosity mPa.s | Starting pressure gradient MPa/m |
|-----------|-------------------------------|--------------|-----------------|-------------------------------|
| Dong161   | 1.034                         | 11.797       | 1.1             | 0.153                         |
|           | 1.034                         | 11.797       | 0.5             | 0.067                         |
|           | 1.03                           | 11.797       | 0.4             | 0.053                         |
|           | 1.034                          | 11.797       | 1               | 0.126                         |
|           | 1.034                          | 11.797       | 0.3             | 0.053                         |
| Shu131    | 0.75                           | 10.098       | 1.1             | 0.197                         |
|           | 0.75                           | 10.098       | 0.8             | 0.079                         |
|           | 0.75                           | 10.098       | 0.5             | 0.043                         |
|           | 0.75                           | 10.098       | 0.3             | 0.034                         |
|           | 0.097                          | 8.163        | 1.1             | 0.408                         |
|           | 0.097                          | 8.163        | 0.5             | 0.185                         |
|           | 0.097                          | 8.163        | 0.4             | 0.148                         |
|           | 0.097                          | 8.163        | 0.3             | 0.116                         |
| Jin251    | 0.316                          | 11.51        | 3.8             | 0.088                         |
|           | 0.316                          | 11.51        | 2               | 0.044                         |
|           | 0.316                          | 11.51        | 1.8             | 0.056                         |
|           | 0.316                          | 11.51        | 1.6             | 0.076                         |
|           | 0.316                          | 11.51        | 1.4             | 0.031                         |

The fitting results are as follows:

![Figure2](image1.png)  ![Figure3](image2.png)

Figure2. The fitting results of Dong 161 well and Shu 131 well  Figure3. The Fitting results of Jin 251 well
The above figure shows that the starting pressure gradient is related to permeability, porosity of rock and the viscosity of fluid. The starting pressure gradient increases with the increase of porosity and fluid viscosity, and decreases with the increase of permeability.

5. Relationship between start-up pressure and other physical properties
In the capillary pore model, the velocity of flow is constant, and in the process of boundary fluid seepage, the driving force is balanced with the capillary resistance. The equilibrium equation is as follows:

$$\Delta P \cdot \pi r^2 - (\tau_0 + \mu \frac{dV}{dr}) \cdot 2\pi r L = 0$$

where, $\Delta P$ is the driving pressure difference at both ends of the capillary, $\tau_0$ is the fluid yield stress value, $\mu$ is the fluid viscosity, $v$ is the fluid seepage velocity, and the $L$ is the capillary length.

Using the above formula, the flow formula of fluid with yield value through capillary tube can be deduced, that is:

$$\bar{v} = \frac{r^2 (\Delta P - \frac{8L \tau_0}{3r})}{8\mu L}$$

Change the upper formula to:

$$\bar{v} = \frac{r \Delta P}{4\mu 2L} - \frac{\tau_0 r}{3\mu}$$

The $\tau_0$ of shear stress at the pipe wall is:

$$\tau = \frac{r \Delta P}{2L}$$

The laminar state of a plastic fluid is similar to that of a Newtonian liquid, so there are:

$$\mu \frac{dV}{dr} = \frac{r \Delta P}{2L}$$

Replace (6) with (4) to:

$$\mu \frac{dV}{dr} = \frac{4\mu (\bar{v} + \frac{r \tau_0}{3\mu})}{r} + \tau_0$$

Replace (5) and (7) with (3) to:

$$\frac{r \Delta P}{2L} = \frac{4\mu (\bar{v} + \frac{r \tau_0}{3\mu})}{r} + \tau_0$$

The mathematical expressions of seepage velocity, yield $Q$ and core cross-sectional area $A$ core are as follows:

$$\bar{v} = \frac{Q}{\phi A}$$

The relationship permeability $K$ and capillary radius of rock $r$ is as follows:

$$K = \frac{\phi r^2}{8}$$

Form (10), (11) and (9) are arranged:

$$\bar{v} = \frac{K}{\mu \phi} \left( \frac{\Delta P}{L} - \frac{7\tau_0}{3\sqrt{2} \sqrt{\frac{\phi}{K}}} \right)$$
The formula (12) is the seepage law of unidirectional fluid in low permeability reservoir.

6. Conclusion

Through research and analysis, the following conclusions are drawn:

(1) In this paper, the starting pressure gradient formula is obtained by combining theory with experiment, and the starting pressure gradient is related to permeability, and other physical properties such as viscosity and porosity.

(2) The experimental results show that the ultimate shear stress increases with the increase of viscosity, which is proportional to the ultimate shear stress. Therefore, it is assumed that the fluid properties have an effect on the starting pressure gradient and viscosity, that is, the starting pressure is proportional to the fluid viscosity.

(3) It can be seen from the calculation formulas that the seepage velocity is affected by reservoir porosity, permeability, oil supply radius and fluid ultimate dynamic shear stress.

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