The physicochemical mechanism and mathematical model of the pseudo-four-phase flow in the movable gel system

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Abstract. The movable gel system (MGS) has the dual function of "regulation" and "flooding", which has been carried out in a large number of pilot test and industrial application. Laboratory experiments and field test results show that approximate solid particles exist in MGS which is different from the aqueous phase and have the seepage characteristics of "blocking but never shutting off", the micro reason is the presence of movable gel transform into gel particles. Therefore, this paper divided MGS into two parts of movable gel and gel particles, and we established mathematical model of the pseudo-four-phase flow for MGS, built relatively comprehensive characterization methods for MGS; the gel particles are regarded as separate phase which differ from the oil, gas and water phase, we proposed the pseudo-four-phase flow model and the method for the treatment of the relative permeability of the pseudo-four-phase flow. The new pseudo-four-phase seepage mathematical models is closer to the actual field seepage characteristics and improve the accuracy of the results for MGS simulation, this is an important work of scientific guidance for the industrial promotion of MGS.

1. Introduction

Movable gel profile control system includes the advantages of near well profile control and polymer flooding [1, 2]. The system is composed of polymer and crosslinking agent in a certain ratio, also known as CDG, weak gel, crosslinking polymer solution, deep profile control agent and so on [3]. It performs both highly viscous of the gel and the fluidity of polymer solution, has a very good deformation ability and pore plugging effect [4].

Major oil fields in China have conducted pilot tests and industrial application study of MGS and have accumulated lots of laboratory data and field implementation data. Laboratory studies have proved the phenomenon that movable gel is able to transform into gel particles. Consequently, it contains approximate solid particles, of which the percolation characteristics are different from water phase. But this significant distinction has not yet been applied to the characteristic equation or numerical simulation method. Therefore, current “oil-gas-water” three phase flow theory is unable to reflect the characteristic of MGS [5-10]. The simulation mechanisms and results of the system based on the old theory will not fit the field application.
To fill the research gap mentioned in last paragraph, this paper considers MGS as two parts of movable gel and gel particles based on microscopic experiment results in Section 2. In Section 3, this paper also gives out a computation method for relative permeability of pseudo-four-phase flow. In Section 3, a numerical model is established to fit the core displacement experimental data to validate the whole method.

2. Microscopic characteristic of MGS
The field application has verified the characteristic of “blocking but never shutting off” of MGS. Chinese scholars figure out by studying the micro mechanism from experimental data and field data, that movable gel system has the displacement mechanism of “migration-blocking-remigration” and the phase transition characteristic of “Amoeba” during flowing through porous media.

This paper verified former achievements by sand-packed experiment, shown in Figure 1. At the beginning of the displacement, movable gel system move through a short distance, the concentration of system is high, contains large gel particles; in the middle of the term, the concentration decreases, and the number of particles gets lower, also the size of particles become smaller; in the later period, the concentration continuously gets down, and there are fewer particles; in the end of the displacement, particles no longer exist, the concentration of the system is at a particular low level.

![Figure 1. Picture of gel particles from different section in the sand-packed pipe.](image)

During the process of flowing through the porous media, the movable gel system deforms and smashes into pieces naturally. It is substantially the process of movable gel transform into gel particles, and this process shows the characteristic of “Amoeba”. The displacement characteristic of “migration-blocking-remigration” is that movable gel and particles transform into each other due to the change of concentration. When concentration is high, it will transform into gel particles, the particles play the role of plugging the pores. When concentration is low, it will transform into movable gel and contribute to profile control. Therefore, in next section, we establish the corresponding equation to describe this phenomenon by chemical reaction and relative permeability.

3. Characterization methods of pseudo-four-phase flow

3.1. Chemical reactions
Types of polymer crosslinking reaction system are numerous, sums up into three categories as: a) transition metal crosslinking system under the effects of carboxylic acid groups of the polymer molecules and transition metal ions, such as chromium, zirconium and aluminium, b) aldehyde crosslinking system under the effects of amide groups of polymer molecules and aldehyde material (mainly formaldehyde), and another one kind, c) composite crosslinking system which combines both advantages of the former systems.

At present, only the crosslinking reaction kinetics model of transition metal crosslinking system is partly presented, models of the other two kinds of crosslinking system are still in the experiment stage.
Take transition metal ion chromium as an example, its chemical reaction equations describe as follows:

\[
\begin{align*}
\text{nCr}^{3+} + \text{polymer} & \rightarrow \text{mg} \quad (C_{\text{mg}} \leq C_{\text{mgmax}}) \\
\text{nCr}^{3+} + \text{polymer} & \rightarrow \text{Gel} \quad (C_{\text{mg}} > C_{\text{mgmax}}) \\
\text{mg} & \rightarrow \text{Gel} \quad (C_{\text{mg}} > C_{\text{mgmax}})
\end{align*}
\]

(1)

According to the equation, we can conclude that after the crosslinking reaction, the MGS can be divided into movable gel and gel particles, which agreed with the result of microscopic displacement experiment in the porous media for MGS.

Thus the reaction kinetics characteristics equation of the generative process can be described as follows:

\[
\begin{align*}
R^+_{\text{mg}} &= \frac{d[\text{Gel}]}{dt} = -\frac{1}{n} \frac{d[\text{Cr}^{3+}]}{dt} \quad (C_{\text{mg}} \leq C_{\text{mgmax}}) \\
R^-_{\text{mg}} &= \frac{d[\text{mg}]}{dt} = -K \frac{d[\text{mg}]}{dt} \quad (C_{\text{mg}} > C_{\text{mgmax}}) \\
R^+_{\text{gel}} &= \frac{d[\text{Gel}]}{dt} = -\frac{1}{n} \frac{d[\text{Cr}^{3+}]}{dt} \quad (C_{\text{mg}} > C_{\text{mgmax}})
\end{align*}
\]

(2)

Temperature, pH value, shear and ionic concentration can all lead to the degradation of movable gel. In addition, the process of reaction varies with time, makes the reduction of gel particles strength. The characterization equation for this process is:

\[
R^-_{\text{gel}} = \frac{dS_{\text{gel}}}{dt} = -K_d \cdot S_{\text{gel}}
\]

(3)

3.2. Relative permeability

Taking the relative flow of gel particles into account, we established the description of four phase relative permeability. The relative permeability curve of the oil phase and gaseous phase were still considered as three phase permeability, additionally added one curve of relative permeability of gel particles and amended the relative permeability curve of the water phase.

On the basis of relative permeability curves of oil-water and oil-gas by experiment data, we assumed that the permeability of wetting phase and non-wetting phase are only functions of saturation, then the relative permeability of water and gas in the four-phase seepage model can be directly read from the relative permeability curves of oil-water and oil-gas or be calculated of interpolation from the curves separately. And the relative permeability of the middle wetting phase oil phase can be calculated from the Stone formula:

\[
K_{ro} = K_{rsw} \left[ \frac{K_{rsw} + K_{rw}}{K_{rsw} + K_{rw}} \right] = K_{rsw} - K_{rw}
\]

(4)

The average pore-throat radius decreases when the wetting saturation increases. As the average pore-throat radius turns to be lower than the hydrodynamic radius of the movable gel (corresponds to the
saturation $S'_{gel}$), the gel particles will lose the ability of flowing. The relative permeability curve of gel particles can be expressed as:

$$K_{gel} = \begin{cases} K_{w0} & (S_w \leq S'_{gel}) \\ 0 & (S_w > S'_{gel}) \end{cases}$$  \hspace{1cm} (5)

The correction equation of water phase relative permeability curve is:

$$K_{rw} = \begin{cases} K_{gel} & (S_w \leq S'_{gel}) \\ K_{w0} - K_{gel} \left( S'_{gel} \right) & (S_w > S'_{gel}) \end{cases}$$  \hspace{1cm} (6)

Fig.2. shows the diagram of the relative permeability in the four-phase flow model.

![Relative Permeability Diagram](image)

**Figure 2.** The relative permeability in the four-phase percolation model.

### 4. Result analysis

According to the parameters of injection and production adopted in the experiment, the water-cut, the injection pressure and the oil recovery curve (Figure 3) are calculated by the newly established mathematical model in section 3. During the calculation, the residual resistance coefficient of copolymer produced in the core is unknown and is obtained by fitting the subsequent water-flooding pressure. Compared with the experimental results, the results of numerical simulation can better reflect the process of pressurization and water shut-off of sealing channeling system. The subsequent water-flooding pressure is about 1500 kPa and the water-cut funnel is obviously. Table 1 shows the comparison of experimental result and calculated result. When the water-cut rises to 91.1%, the corresponding oil recovery is 23.7%. After the injection of modified starch gel, the water-cut decreases to 63.4%, the corresponding oil recovery is 26.4%, the corresponding staged oil recovery is 2.5% and the injection pressure increases to 221 KPa. The water-cut reaches to 96.9% when injected modified starch gel volume is 1.88PV, the corresponding oil recovery is 43.0% and the corresponding staged oil recovery is 17.3%. The residual resistance coefficient of copolymer obtained by fitting is 350, much larger than the conventional gel.
Figure 3. Curves comparison between experiment results and calculation results.

Table 1. Parameters comparison between experiment results and calculation results.

| Results         | The first water flooding stage | Injection stage of modified starch gel system | The secondary water flooding stage |
|-----------------|-------------------------------|---------------------------------------------|-----------------------------------|
|                 | Recovery /%                   | Level recovery /%                           | Injection pressure /KPa            |
| Experiment      | 25.9                          | 27.7                                        | 65.0                              |
| Calculation     | 23.7                          | 26.4                                        | 63.4                              |

5. Conclusion

The main understandings are as follows.

(1) Microscopic experiments proved that movable gel system in porous media can be divided into two different fluids: movable gel and gel particles, with clear interface, different viscosities and percolation properties, and with the change of concentration, the two fluids can be transformed into each other. The transformation process of gel particles intuitively reveals the change of movable gel system in field test and the percolation mechanism of “rise and then fall” of injection pressure.

(2) On the basic law of microcosmic distribution and migration of oil and water in porous media, we established a relative permeability model with a comparatively clear interface, but no strict phase interface, and gave out the handling method and characterization method of pseudo-four-phase relative permeability, built a mathematical representation method for the percolation characterization of "approximate solid particles", which is a reference for the study of the porous media transport theory about grain plugging agent.

(3) According to the parameters of injection and production adopted in the experiment, the water-cut, the injection pressure and the oil recovery curve are calculated by the newly established mathematical model. Compared with the experimental results, the results of numerical simulation can better reflect the process of pressurization and water shut-off of sealing channeling system.
6. Nomenclature

Table 2. Nomenclature

| Symbol | Description |
|--------|-------------|
| $Cr^{3+}$ | The crosslinking agent. |
| $mg$ | The movable gel produced in the reaction. |
| $Gel$ | The gel particles. |
| $C_{mg}$ | The concentration of movable gel, $\mu g/cm^3$. |
| $C_{mg_{\text{max}}}$ | The critical concentration of movable gel, $\mu g/cm^3$. |
| $K_1, K_2, K_3$ | The equivalent ratio between crosslinking agent and polymer, measured by experiment. |
| $l$ | The reaction order, determined by the experiment. |
| $-$ | The consumption of quality. |
| $K_d$ | The degradation constant, measured by experiment. |
| $S_{gel}$ | The saturation of gel particles. |
| $K_{ro}$ | The relative permeability of oil phase. |
| $K_{rocw}$ | The relative oil phase permeability of bound water. |
| $K_{row}$ | The corresponding relative oil phase permeability on the oil-water relative permeability curve. |
| $K_{rw}$ | The water phase relative permeability. |
| $K_{rog}$ | The corresponding relative oil phase permeability on the oil-gas relative permeability curve. |
| $K_{rg}$ | The gas phase relative permeability. |
| $K_{rw}$ | The water phase relative permeability. |
| $K_{rgel}$ | The relative permeability of gel particles. |
| $K_{rw0}$ | The water phase relative permeability in the three-phase percolation model. |
| $S_w$ | The saturation of water phase. |
| $S'_{gel}$ | The critical saturation when the gel particles become unable to flow. |
| $K_{rw}$ | The water phase relative permeability in the four-phase percolation model. |

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