ADVANCES IN PETROLEUM EXPLORATION AND DEVELOPMENT
Vol. 1, No. 1, 2011 PP. 50-58
ISSN 1925-542X [PRINT]
ISSN 1925-5438 [ONLINE]
www.cscanada.net
www.cscanada.org

Investigation of Blocking Characteristics by Particles in Heterogeneous Reservoir

WANG Jing[1,*]; LIU Huiqing[1]; XU Jie[1]; YAN Fenglin[1]; WANG Mingchun[2]

[1] Key Laboratory for Petroleum Engineering of the Ministry of Education, China University of Petroleum, Beijing 102249, China
[2] CNOOC Research Institute, Beijing 100027, China

* Corresponding author. Email: wangjing8510@163.com

Abstract: A mathematical model of suspension filtration in porous media has been established based on mass conservation principle and characteristics of particles depositing and blocking. On this basis, percolation rules and blocking characteristics of suspension in heterogeneous reservoir were investigated. It is showed that suspension injection could remarkably reduce the permeable ratio and improve the heterogeneity significantly. Low-speed and low-viscosity injection could achieve shallow profile control, and high-speed and high-viscosity injection could achieve deep profile control. Adjusting the injection rate or viscosity of carrying fluid slug at the right time to make the particle retention concentration profile in thief zones and the water-flood front keep consistent could achieve dynamic profile control. For the reservoirs without a good interlayer, the optimum injection rate and viscosity of carrying fluid were chosen based on the connectivity of layers, and in the reservoirs with good interlayers the injection rate and viscosity should be lowered appropriately under the field permitting conditions. When the suspension concentration was constant, the instantaneous fractional flow of high permeable layer first decreased sharply and then ramped up with the increasing injection volume. Initial percolation coefficient is the basis of a high utilization of suspension and a good result in profile control.

Key words: Heterogeneous reservoir; Suspension; Percolation; Profile control; Retention concentration; Blocking characteristics

Nomenclature

C	Concentration of suspension, m^3/m^3;	λ	Percolation coefficient, m^{-1};
V	Seepage velocity, m/s;	λ_0	Initial percolation coefficient, m^{-1};
Δ	Retention concentration of particles, m^3/m^3;	x, y, z	Index, dimensionless;
Φ	Porosity, dimensionless;	α	Parameter, dimensionless;

† Received 20 April 2011; accepted 6 June 2011. **DOI:** 10.3968/j.aped.1925543820110101.006

δ_{max} Ultimate retention concentration, m^3/m^3;

φ_c Porosity of particles;

k_0 Initial permeability, $10^{-3}\mu m^2$;

$k(x, t)$ Current permeability, $10^{-3}\mu m^2$;

G Fraction of pore space containing pluggable pathways, dimensionless;

β, n_1, n_2 Parameters;

$\varphi(x,t)$ Instantaneous porosity, dimensionless;

Q Injection rate, cm^3/s;

Δp Pressure drop, MPa;

μ_f Viscosity of carrying fluid, mPa s;

A Area, m^2;

L Distance from injector to producer, m;

Q_t Total injection rate, cm^3/s;

Q_i Injection rate of layer i，m^3/s;

k_i Permeability of layer i, $10^{-3}\mu m^2$;

k_H Permeability of high permeable layer, $10^{-3}\mu m^2$;

k_L Permeability of low permeable layer, $10^{-3}\mu m^2$;

μ_i Fluid viscosity of layer i, mPa s;

A_i Area of layer i, m^2;

$\bar{\mu}(t)$ Instantaneous fluid viscosity, mPa s;

$\bar{k}(t)$ Instantaneous permeability, $10^{-3}\mu m^2$

1. INTRODUCTION

At the high water-cut stage, the problem of heterogeneous reservoirs is that the injected water channels into producer wells through high permeable layers which will induce the futile cycle of displacement fluid. Also, the long-term scouring action on the high permeable layer will intensify the heterogeneity and make it easier for the injected water to channel into the production well through the high permeable layer. Therefore, it is necessary to decrease the permeability of high permeable layer, which will increase the intake capacity of low permeable layers and displace out numerous residual oil. As early as 60s in the 20th century, United States and the Soviet Union began to adjust the intake profile of heterogeneous reservoirs by injecting suspension (Chen, Y.P. and Xie, S.X. 1980). The reason is that a large number of suspended particles flow into high permeable layers preferentially and retain in it under the action of many forces, which will decrease the porosity and permeability of high permeable layers. At the same time, the suitability is better than any other plugging agents in high-temperature and high-salinity reservoirs (Zhang, G.Y., et al. 2007). At the present time, drilling mud filtration, formation damage of waste water re-injection and permeability decreasing for sand production are all the focal points of the study of suspension percolating in reservoirs. However, the percolation characteristics of particles in the deep reservoir are rare (Zhang, H.L. and Liu, H.Q. 2007). In order to achieve well blocking effect of high permeable layer but not damage the low permeable layer, the investigation of filtration laws and blocking characteristics by particles in heterogeneous reservoir is very significant.

2. MECHANISMS OF PROFILE CONTROL BY SUSPENSION IN HETEROGENEOUS RESERVOIR

When suspension flows through porous media, a part of particles flow with the liquid, and the other part will be separated from the liquid. So, the two states of particles mobilization and retention exist. Particles retention is classified into smooth surface deposition, size exclusion and pore bridging (Wennberg, K.E., Batrouni, G., and Hansen, A. 1995; Gruesbeck, C. and Collins, R.E. 1982; Ohen, H. A. and Civan, F. 1989), which are the three basic mechanisms.

a. Smooth surface deposition whereby particles are attracted to the pore surface by van der Waals force, electrical double layer repulsion, Bonn short-range repulsion, fluid drag force, and in some cases gravitational forces. In this way, it reduces permeability through porosity reduction.

b. Size exclusion whereby a particle is trapped at a pore throat that is smaller than the particle. In this way, the pore diameter and flowing area are reduced, so the permeability greatly reduced.

c. Pore bridging whereby two or more particles are small enough to go through a pore throat and come together to bridge the pore. It also reduces the flowing area, but the degree is lower than size exclusion and needs a higher concentration.

At the late stage of heterogeneous reservoirs development, the flooding fluid mainly channels to production wells along the high permeable layers, and the sweep efficiency of layers with low to medium permeability is very low or even non-effective, so there is still a lot of remaining oil in these layers. In order to enhance the oil recovery, it is needed to improve the injection profile and increase water intake capacity of low permeable layers, so that the remaining oil will be flooded out. Because the permeability and fluid property are different in different layers, most of suspension flows into the high permeable layers, and particles retain in it. As a result, the permeability of high permeable layers greatly reduces, and the fractional flow of the layers with low to medium permeability increases, so lots of remaining oil is displaced out.

3. PERCOLATION MODELS OF PARTICLES IN POROUS MEDIA

3.1 Dynamical Equation of Particles

The channeling between injector and producer can be regarded as unidirectional flow because the channel is narrow and the vertical heterogeneity is far stronger than areal one. When the diameter of a particle is larger than 1μm, the diffusion can be neglected. Based on the law of conservation of mass, the continuity equation that particles flow in porous media will be:

$$v\frac{\partial c}{\partial x}+\frac{\partial}{\partial t}(\phi c+\delta)=0 \tag{1}$$

Due to the particles retaining in porous media is much less than that flow through it, the changes of concentration and porosity that causes by retentive particles is very little, and $\partial(\phi c)/\partial t=0$ (Dou, J.H. and Fu, Y. 2002; Alvarez, A.C. 2007). Then the Eq.1 can be simplified:

$$-v\frac{\partial c}{\partial x}=\frac{\partial\delta}{\partial t} \tag{2}$$

When suspension flows through porous media, the gradient separation takes place between solid and liquid phase. Some particles are adsorbed and trapped by porous media, and the suspension concentration is the function of percolation distance and time. Ives proposed the following relation (Ives, K.J., 1960):

$$\frac{\partial c(x,t)}{\partial x}=-\lambda c(x,t) \tag{3}$$

Combining Eq.2 and Eq.3,

$$\frac{\partial\delta}{\partial t}=\lambda v c(x,t) \tag{4}$$

In fact, the percolation coefficient (λ) is not constant (Dou, J.H. and Fu, Y. 2002). It is concerned with the pore structure, specific area of pore, flow velocity, fluid viscosity, particle features and current retention levels (Zhang, H.L. and Liu, H.Q. 2007; Wang, B.X., Li, C.H., and Peng, X.F. 2003). Ives (1969) proposed the following general formula,

$$\lambda=\lambda_0\left(1+\frac{\alpha\delta}{\phi_0}\right)^x\left(1-\frac{\delta}{\phi_0}\right)^y\left(1-\frac{\delta}{\delta_{\max}}\right)^z \tag{5}$$

The first term represents the action that particles deposit on the pore surface, which makes the diameter of the filtration pores decrease and the pore structure be complicated, then the filtration capacity increases. he second term represents the decreasing filtration capacity, which is caused by the decreasing pore specific area due to the surface deposition. The third term represents the influence of current retention levels, ultimate filtration capacity, flow velocity and fluid viscosity on the percolation coefficient. The initial percolation coefficient (λ_0) reflects the effect of particles and pore surface properties, so it is constant for specific particles and porous media. In order to simplify the calculation, the first two actions are similar to be cancelled out, and the index of the third term equals 1(z=1) (Maroudas, A. and Eisenklam, P. 1965). Thus,

$$\lambda=\lambda_0\left(1-\frac{\delta}{\delta_{\max}}\right) \tag{6}$$

Ultimate retention volume is a function of fluid viscous force (f_v) which equals the product of flow velocity (v_f) and fluid viscosity (μ_f). The larger the flow velocity and fluid viscosity are, the less the ultimate retention volume is. Some studies indicate that there exists an exponential relation between ultimate retention volume and fluid viscosity for a specific fluid (Bedrikovetshy, P. et al. 2010). However, the carrying fluid is not always water.

Sometimes, it may be polymer solution or viscous water. Therefore, the ultimate retention volume can be expressed as a function of fluid viscous force,

$$\delta_{\max}(v_{\mathrm{f}},\mu_{\mathrm{f}}) = \delta_{\max}\big|_{v_{\mathrm{f}}=0,\mu_{\mathrm{f}}=\mu_{\mathrm{w}}} \cdot \exp(-f_{\mathrm{v}}^{\,n}) \tag{7}$$

$$f_{\mathrm{v}} = \mu_{\mathrm{f}} v_{\mathrm{f}} \tag{8}$$

The ultimate retention volume approximately equals the porosity. Considering the existed clearance among the particles, the φ_{c} is introduced to characterize it, and the ultimate retention volume can be modeled as following,

$$\delta_{\max}\big|_{v_{\mathrm{f}}=0,\mu_{\mathrm{f}}=\mu_{\mathrm{w}}} = \phi_0(1-\phi_{\mathrm{c}}) \tag{9}$$

3.2 Solution and Application of this Model

3.2.1 Model Solution

According to the percolation characteristics, the initial and boundary condition will be：

$$c(x,t)\big|_{x=0} = C_0\,, \quad \delta(x,t)\big|_{t=0} = 0 \tag{10}$$

Combined Eq.2, Eq.3, Eq.6, Eq.7 and Eq.10 to form a complete model as Eq.11,

$$\begin{cases} -v\dfrac{\partial c}{\partial x} = \dfrac{\partial \delta}{\partial t} \\ \dfrac{\partial c}{\partial x} = -\lambda c \\ \lambda = \lambda_0\left(1-\dfrac{\delta}{\delta_{\max}}\right) \\ \delta_{\max}(v_{\mathrm{f}},\mu_{\mathrm{f}}) = \delta_{\max}\big|_{v_{\mathrm{f}}=0,\mu_{\mathrm{f}}=\mu_{\mathrm{w}}} \cdot \exp(-f_{\mathrm{v}}^{\,n}) \\ c(x,t)\big|_{x=0} = C_0, \delta(x,t)\big|_{t=0} = 0 \end{cases} \tag{11}$$

Then, the distribution of suspension concentration and particles retention concentration can be obtained, which is shown as following:

$$c(x,t) = \frac{c_0}{1-\exp\left[-\dfrac{\lambda_0 v c_0 t}{\phi_0(1-\phi_{\mathrm{c}})\exp(-f_{\mathrm{v}}^{\,n})}\right] + \exp\left[-\dfrac{\lambda_0 v c_0 t}{\phi_0(1-\phi_{\mathrm{c}})\exp(-f_{\mathrm{v}}^{\,n})} + \lambda_0 x\right]} \tag{12}$$

$$\delta(x,t) = \frac{\phi_0(1-\phi_{\mathrm{c}})\exp(-f_{\mathrm{v}}^{\,n})\left\{1-\exp\left[-\dfrac{\lambda_0 v c_0 t}{\phi_0(1-\phi_{\mathrm{c}})\exp(-f_{\mathrm{v}}^{\,n})}\right]\right\}}{1-\exp\left[-\dfrac{\lambda_0 v c_0 t}{\phi_0(1-\phi_{\mathrm{c}})\exp(-f_{\mathrm{v}}^{\,n})}\right] + \exp\left[-\dfrac{\lambda_0 v c_0 t}{\phi_0(1-\phi_{\mathrm{c}})\exp(-f_{\mathrm{v}}^{\,n})} + \lambda_0 x\right]} \tag{13}$$

3.2.2 Model Application

A majority of suspension flows into high permeable layers. And a part of particles separate from liquid phase and retain in porous media to decrease the permeability. According to the blocking—non-blocking parallel path PDE model (Gruesbeck, C. and Collins, R.E. 1982) and the empirical relationship of permeability in blocking and non-blocking paths (Civan, F. 1994), the influence of surface deposition and pore blockage is treated separately. Based on equivalent percolation theory, the permeability after suspension flowing through will be:

$$\frac{k(x,t)}{k_0} = G\cdot\exp\left[-\beta\delta(x,t)^{n_1}\right] + (1-G)\left[\frac{\phi(x,t)}{\phi_0}\right]^{n_2} \tag{14}$$

The porosity after particles retaining will be:

$$\phi(x,t) = \phi_0 - \delta(x,t) \tag{15}$$

According to Darcy's law,

$$Q = \frac{kA\Delta p}{\mu L} \tag{16}$$

The total injection volume is the sum of the branched injection volume of each layer,

$$Q_t = \sum_{i=1}^{n} Q_i \tag{17}$$

And the branched injection volume is,

$$Q_i = \frac{k_i A_i / \mu_i}{\sum_{i=1}^{n} k_i A_i / \mu_i} Q_t \tag{18}$$

The permeability and fluid viscosity along the way is not constant, so the average mobility is used to calculate the branched injection volume. According to principle of hydroelectricity similarity and equivalent percolating resistance theory, the average mobility between injector and producer is,

$$\frac{\bar{\mu}(t)}{\bar{k}(t)} = \frac{1}{L}\int_0^L \frac{\mu(x,t)}{k(x,t)} dx \tag{19}$$

4. BLOCKING CHARACTERISTICS BY PARTICLES IN HETEROGENEOUS RESERVOIRS

4.1 Dynamical Analysis of Blocking Characteristics by Particles

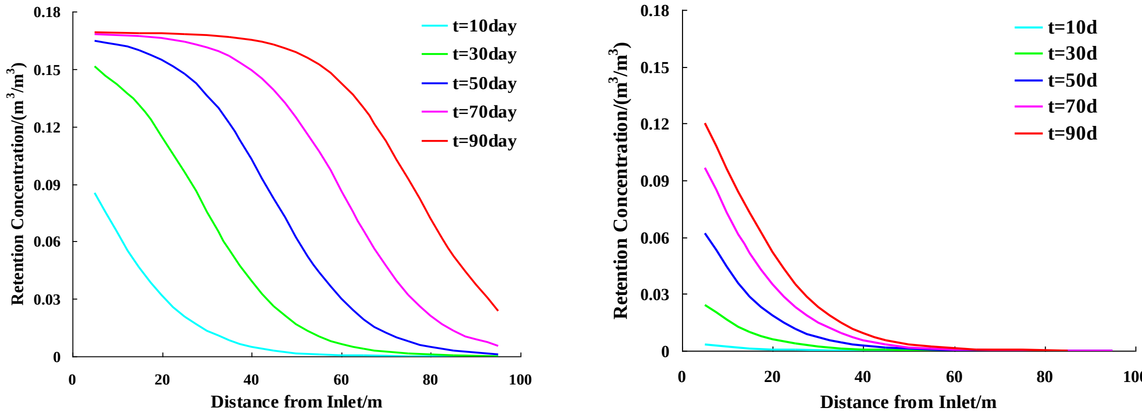
In order to study the filtration laws and blocking characteristics of suspension in heterogonous reservoirs, a reservoir model with vertical heterogeneity is built. Due to the screening effect, the water channeling is supposed to occur only between two adjacent wells. After the water flooding over a long time, the fluid-flow in thief zones can be seemed as a single water-phase flow and the fluid-flow in low permeable layers which are not swept by water can be seemed as a single phase (oil) flow since. Because the vertical heterogeneity is much larger than plain heterogeneity, the injected water storms down the producers along the main streamlines of channels, and the channeling path is quite narrow, the channeling can be seen as one dimensional flow. Based on the fact discussed above we propose that : (a) the variation of percolation flow velocity influences the coefficient of percolation in an instant; (b) two-phase flow in less permeable layers can be seen as piston water flooding; (c) only layer flowage is concerned.

In the dynamical simulation model, the suspension with the concentration of 0.1 is supposed to be injected at the rate of 200cm^3/s. The parameters used in the model are shown in table 1.

Tab. 1: Parameters Used in the Model

k_H /μm^2	k_L /μm^2	μ_o /mPa s	μ_w /mPa s	L /m	A_i /m^2	λ_0 /m^{-1}	G	φ_0	n	φ_c	β	n_1	n_2
5	0.5	5	1	100	10	0.001	0.3	0.25	1	0.2	100	0.8	3

Fig.1 (a) and Fig.1(b) show how the retention concentration changes with distance away from injector at different times in both high and low permeable layers. It is clear that the particle concentration is high and the particles distribute evenly in the high permeable layer. However, in the low permeable layers, particles are almost held up in the area near the injector. At the early injection period, the suspension firstly flows into the thief zones and the particles are mainly held up there leading to a declination of the permeability. The low permeable layer remains the same for little suspension flowing into it, so the formation heterogeneity is improved. After a period of time, as the fractional flow in the low permeable layer increases, more particles are held up and the particle concentration profile advances to the deep reservoir. The particle concentration in thief zones reaches to a peak value when the speed of retention and remigration are equal, and in this case more suspension will damage the low permeable layer since more particles will be held up in it to reduce the permeability.

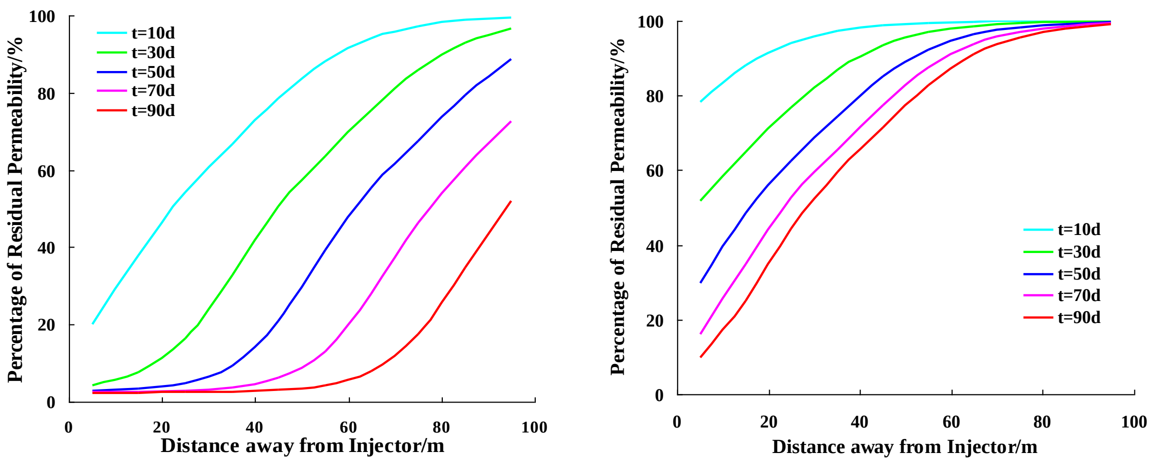


(a) High permeable layer (b) Low permeable layer

Fig. 1: Retention Concentration Changes with Distance away from Injector at Different Times

In this paper, the ratio of the permeability after injecting suspension to the initial permeability is defined as the percentage of residual permeability. Fig.2 (a) and Fig.2 (b) show the percentage of residual permeability changes with the distance from the injector in both high and low permeable layers at different times. It shows that the suspension effectively reduces the permeability to less than 10% of its initial value of thief zone. However, the permeability in low permeable layer almost doesn't change except in a small area around the injector. As a result, the permeability ratio of the reservoir decreases from 10:1 to 1.5:1. So the residual oil in low permeable layer becomes producible by water flooding.

Fig.3 shows retention concentration changes with distance away from injector when a 2PV of suspension is injected at different rates. It is clear that the particle concentration decreases sharply from 0.2 near the injector to almost 0 in the area more than 50m away from injector when the injection rate is low. However, when the injection rate is high, the particles can be taken along much further and the particle concentration remains high in deep reservoir. In this case, profile control near wells can be achieved by injecting suspension at a low rate while deep profile control in a reservoir can be achieved by injecting suspension at a high rate. As for a severely heterogeneous reservoir with interkyer channeling, the injection rate should be low at the early stage, as the water-flood front advances in the low permeable layer, the injection rate should be enlarged to make the particle concentration profile in thief zone and the water-flood front keep consistent. That is how the dynamic profile control is finished.



(a) High permeable layer (b) Low permeable layer

Fig. 2: Percentage of Residual Permeability Changes with Distance away from Injector at Different Times

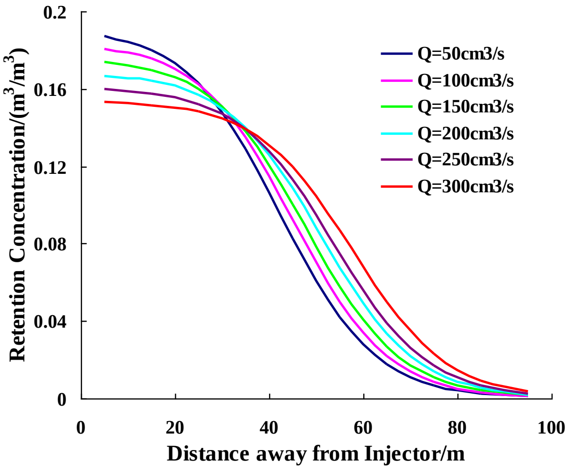


Fig. 3: Retention Concentration Changes with Distance away from Injector at Different Injection Rates

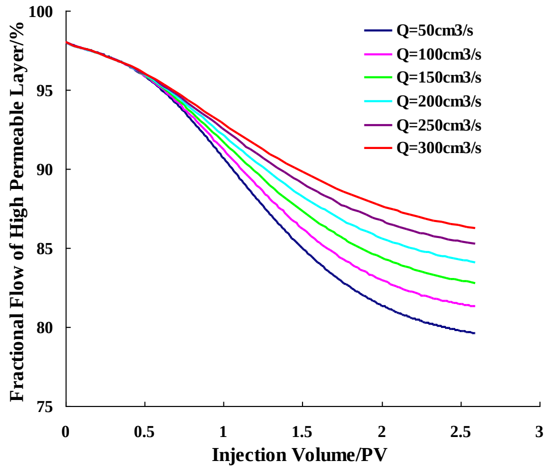


Fig. 4: Fractional Flow of High Permeable Layer at Different Injection Rates

4.2 Sensitive Analysis of Blocking Characteristics by Particles

4.2.1 Injection Rate

The goal of profile control is to increase the fractional flow in low permeable layers to drive the residual oil in them by reducing that in thief zones. Fig.4 shows the fractional flow of high permeable layer at different injection rates. It indicates that the fractional flow decreases faster and more severely when the injection rate is lower since particles are not easily migrate with a lower drag force. However, the particles mainly retain near the injector when injection rate is lower and the permeability changes little in deep reservoir, so severe interkyer channeling may occur in deep reservoir where there is no effective barrier layers. As for a reservoir with effective barriers layers, we can decrease the injection rate to perform better in profile control in the field permitting condition.

4.2.2 Viscosity of Carrying Fluid

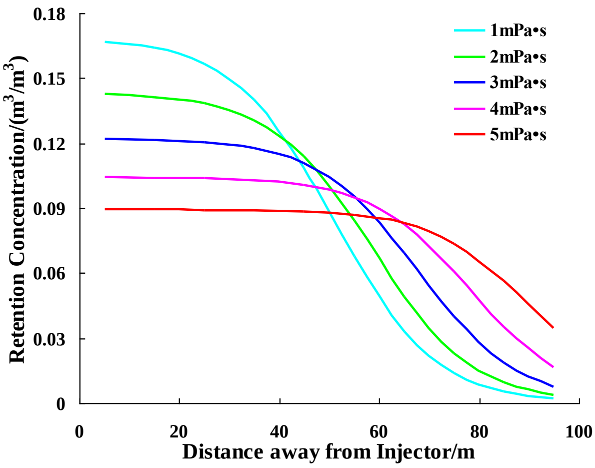


Fig. 5: Fractional Flow Changes with Distance away from Injector for Different Carrying Fluids

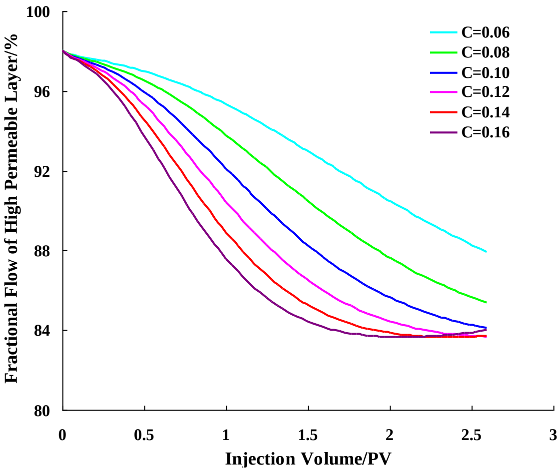


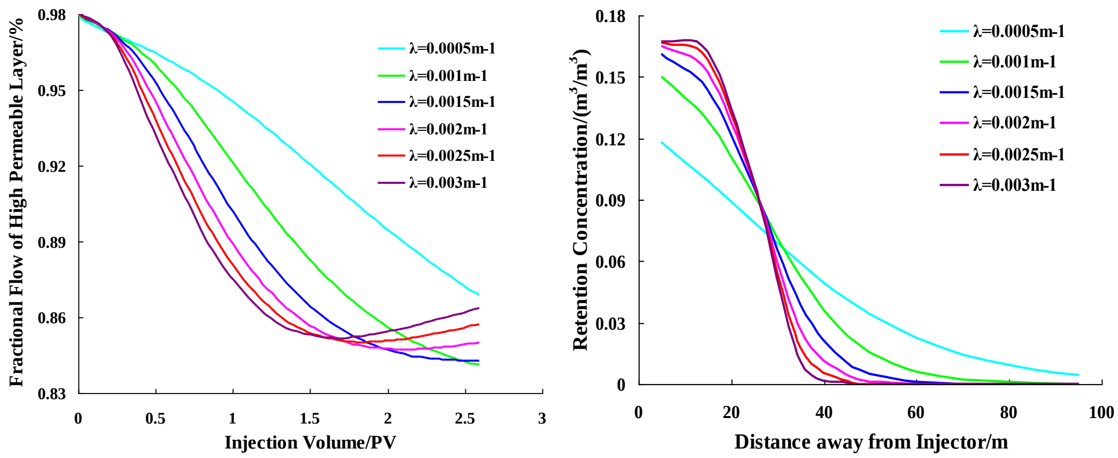
Fig. 6: Fractional Flow of High Permeable Layer Varies with Different Injected Concentrations

Fig.5 shows the fractional flow changes with distance away from injector when viscosities of the carrying fluid are different. It indicates that the overall particle concentration in deep reservoir increases with an increasing viscosity of the fluid though the maximum particle concentration decreases. The reason is that more viscous fluid could carry more particles further to reduce the permeability. So the carrying fluid with high viscosity could be used in deep profile control. What's more, dynamic profile control can be finished by orderly injecting suspension slug with gradually ascending viscosity.

4.2.3 Injection Concentration

Fig.6 shows the fractional flow of high permeable layer changes with different injection concentrations. It can clearly be seen that the fractional flow in high permeable layer decreases faster when the particle concentration is higher and less suspension is needed to make the fractional flow reach its minimum value. From the whole flooding process, the fractional flow in high permeable layer firstly deceases rapidly and then ramps up from its minimum value, so there is an optimal injection volume in pursuing the minimum fractional flow. The reason why this phenomenon occurs is that at the early stage of injecting, particles mainly retain in thief zone and the permeability ratio decreases. Thus, the fractional flow in low permeable layer increases and more retained particles lead to a declination of the permeability and when the permeability decreases faster in the low permeable layer than in thief zone, the fractional flow in high permeable layer ramps up reasonably.

4.2.4 Initial Percolation Coefficient



(a) Fractional flow (b) Retention concentration

Fig. 7: Fractional Flow and Retention Concentration Changes with Distance away from Injector at Different Initial Percolation Coefficients

Fig.7 (a) and Fig.7(b) show how the fractional flow and retention concentration changes with the distance away from injector at different initial percolation coefficients in thief zone respectively. They indicate that the fractional flow decreases faster when the initial percolation coefficient is larger and it reaches the minimum value when λ_0 is $0.001m^{-1}$ and injection volume is about 2.5PV, and under such circumstance, the profile control works best. If λ_0 is high, the particles mainly retain near the injector and deep profile control couldn't be achieved; when the λ_0 is low, more particles will migrate to the deep reservoir with the carrying fluid to achieve the deep profile control. But a too low λ_0 may also lead to a low utilization rate of suspension for particles may advance to production wells. Many factors determine the value of λ_0 including the characteristics of porous media and particles also, so it is needed to choose proper particles for different reservoirs to get the best profile control effect.

5. CONCLUSIONS

The formation heterogeneity can be improved by injecting suspension into heterogeneous reservoir. At the early injecting period, the fractional flow in thief zones is higher than that in low permeable layers and particles retain in thief zones to reduce the permeability while the permeability in low permeable layers changes little. In this case, the permeability ratio decreases greatly and the subsequent water flooding performance becomes feasible. Profile control in the area close to injector can be achieved by injecting suspension with low viscosity at a low rate and deep profile control can be achieved by injecting suspension with high viscosity at a high rate. As for the layers with interkyer channeling, low viscous suspension should be chosen to be injected at a low rate at the early injecting period, and as the water-flood front advances in the low permeable layers, the injection rate or the viscosity of the carrying fluid should be enlarged to make the particle retention concentration profile in thief zones and the water-flood front keep consistent. That is how dynamic profile control is done. The fractional flow in high permeable layers ramps up after decreasing rapidly to its minimum value, so there exists an optimal injection volume in pursuing the minimum fractional flow in high permeable layers. As for a reservoir with good barriers, the injection rate can be decreased to get better results in profile control. A proper initial percolation coefficient λ_0 is the basis of a high utilization of suspension and a good result in profile control, therefore, it is needed to choose proper particles for different reservoirs to get the best result in profile control.

REFERENCES

[1] Alvarez, A.C., Hime, G., Marchesin, D., & Bedrikovetsky, P.G. (2007). The inverse problem of determining the filtration function and permeability reduction in flow of water with particles in porous media. *Transport in Porous Media, 70*, 43-62.

[2] Bedrikovetshy, P., Santos, A., Siqueira, A., Souza, A.L., & Shecaira, F. (2010). Quantitative theory for fines migration and formation damage. *SPE International Symposium and Exhibition on Formation Damage Control held in Louisiana, USA,10-12 February*.

[3] Chen, Y.P., & Xie, S.X. (1980). Study on expanding flooding volume by injecting suspension. *Petroleum Exploration and Development, 6*, 50-60.

[4] Civan, F. (1994). A multi-phase mud filtrate invasion and wellbore filter cake formation model. *SPE International Petroleum Conference & Exhibition of Mexico held in Veracruz, Mexico,10-13 October*.

[5] Dou, J.H., & Fu, Y. (2002). Infiltration system and its mathematical simulation. *Applied Mathematics A Journal of Chinese Universities, 17*(1), 113-120.

[6] Gruesbeck, C., & Collins, R.E. (1982). Entrainment and deposition of fine particles in porous media. *Society of Petroleum Engineering Journal, 22*(6), 847-856.

[7] Ives, K.J. (1960). Simulation of filtration on electronic digital computer. *J. Amer. Water Works Assn, 52*, 933-939.

[8] Liu, S. (1994). Analysis of filtration systems and mathematical model. *Acta Mathematiea Scientia,14*(4), 361-365.

[9] Maroudas, A., & Eisenklam, P. (1965). Clarification of suspensions: a study of particle deposition in granular media. *Chem. Engr. Sci., 20*, 867-873.

[10] Ohen, H.A., & Civan, F. (1989). Formation damage in petroleum reservoirs I: modeling. *Unsolicited. This document was submitted to SPE (or its predecessor organization) for consideration for publication in one of its technical journals. While not published, this paper has been included in the eLibrary with the permission of and transfer of copyright from the author.*

[11] Wang, B.X., Li, C.H., & Peng, X.F. (2003). Stability of nano-particle suspensions. *Journal of Basic Science and Engineering, 11*(2), 167-173.

[12] Wennberg, K.E., Batrouni, G., & Hansen, A. (1995). Modeling fines mobilization, migration and clogging. *European Formation Damage Conference held in The Hague, Netherlands,15-16 May*.

[13] Zhang, G.Y., Song S.W., Zhang Y.Z., & Zhao L. (2007). A new method to quantify permeability adaptability of inorganic grain plugging agents. *China Offshore Oil and Gas,19*(6), 409-411.

[14] Zhang, H.L., & Liu, H.Q. (2007). Percolation performance of suspending profile control agent in reservoir formation. *Journal of Hydrodynamics(Ser.A), 22*(1),113-118.