Experimental Study on the Impacts of Suspended Solid Particles in the Reinjection Water on the Reservoir Damage

Dongdi Cui1,2,*, Aifen Li1,2,a and Xiaoxia Ren1,2,b
1School of Petroleum Engineering, China University of Petroleum (East China), Qingdao, Shandong, 266580, China
2Centre of Multiphase Flow in Porous Media, China University of Petroleum, Qingdao, Shandong, 266580, China

*Corresponding author e-mail: cddwork@163.com, aafenli123@163.com, b394418021@qq.com

Abstract. When the suspended solid particles in the reinjection water enter into the reservoir with different permeability, the reservoir will be damaged in different degrees. Taking the reservoir with high permeability in a block of Shengli Oilfield as an example and based on the analysis results of suspended solids content and particle size in the produced fluid, the damage of artificial core permeability has been studied by injecting three different kinds of particle contents with 2 different particle sizes. Different injection rates have been studied as well. The results show that the damage of the suspended solid particles to the reservoir increases with the increase of the injected pore volume and then reaches to a stable value. The larger the core permeability, the smaller the permeability loss. For the core with same level of permeability, the larger the solid particle content and the larger the particle size, the more serious damage of the reservoir. The injection rate of the suspended solid particle has little effect on the damage of the core. Finally, through the interpolation of minimum curvature, the injection pattern of suspended solid particle solution in different permeability reservoirs has been achieved, which will significantly guide the improvement of water injection performance in the oilfield.

1. Introduction
With the maturation of oilfield, water flooding has been applied in many oilfields in China. And with the increase of water cut, the oilfield waste water production increased as well. Therefore, waste water reinjection has been applied by many oilfields as one of the methods for waste water treatment. Due to the heterogeneity of the formation and the difference of physical properties of the formation fluids, the porosity and permeability of the reservoir rocks increases after long-term water flooding and the reservoir requirements for water quality standards should be appropriately relaxed. For various reasons, the refilled water always contains a certain amount of suspended particles, and its content and particle size are important indicators of water quality, which is an important factor causing reservoir damage [1, 2].

At present, according to domestic scholars, the suspended particles injected into the water will seriously block the pore throat, causing the permeability to drop, and the injection pressure to rise[3, 4]. Studies have shown that suspended particles reservoir blocking is a complex process. Under the effect of fluid, suspended particles will have different plugging forms due to the sizes of the core throat, causing different degrees of damage to the reservoir [5]. The factors mainly include injection conditions, injection solution and reservoir itself. Wang Ningning [6], Jiang Jianfang [7], etc. offered that, the
content and particle size of suspended solids needs to be determined experimentally according to the characteristics of each oilfield.

Based on the physical properties and produced water quality of Shengli Oilfield, this paper designed a large number of laboratory experiments with different flow rates, different suspended solids concentration and particle sizes. Many factors that could cause reservoir damage had been considered. Control standards of re-injection water with solids for Shengli Oilfield was proposed, which has an instructive significance for wastewater re-injection in oilfield production.

2. Experimental Work

2.1. Experimental conditions

2.1.1. Experimental Materials. The porosity and permeability of each small layer of Shengli Oilfield are shown in Table 1. According to the SY/T 5329-2012 standard, the average air permeability of Shengli Oilfield exceeds $600 \times 10^{-3} \mu m^2$, and C4 level (content is $c \leq 10.0 mg/L$, particle is $d \leq 4.0 \mu m$) should be implemented.

| Layer | Φ(averag)/% | kₐ(average)/10⁻³μm² |
|-------|-------------|----------------------|
| Ng³₁   | 33.9        | 815                  |
| Ng³₂   | 34.6        | 1257                 |
| Ng³₃   | 35.6        | 1632                 |
| Ng³₄   | 35.1        | 1830                 |
| Ng⁴₁   | 34.8        | 1240                 |
| Ng⁴₂   | 32.7        | 544                  |
| Ng⁴₃   | 34          | 982                  |
| Ng⁴₄   | 33.2        | 932                  |
| Total  | 34          | 1041                 |
|        | 34.3        | 1189                 |

The cores used in the experiment were artificial cores with permeability of $500 \times 10^{-3} \mu m^2$, $1000 \times 10^{-3} \mu m^2$, $1500 \times 10^{-3} \mu m^2$, and $2000 \times 10^{-3} \mu m^2$. The simulated formation water was prepared according to the formation water of Shengli Oilfield, with a salinity of 6869 mg/L, a density of 0.983 g/cm³ at an experimental temperature of 70°C, and a viscosity of 0.416 mPa·s.

The suspended solid particle solution used in the experiment was prepared from quartz sand of different mesh numbers and a certain volume of simulated formation water. The content and particle size of the suspended solid particles in the experiment are determined by the SYT5329-2012 standard and relevant data of the oilfield site.

2.1.2. Experimental Equipment and Flow. The experimental equipments mainly include high temperature and high pressure reservoir displacement simulation device, ISCO pump, intermediate container with magnetic stirrer and core holders and so on.

The experimental equipments for the damage of suspended solid particle solution to the reservoir is shown in Fig. 1(a). The flow is shown in Fig. 1(b). The prepared suspended solid particle solution is placed in an intermediate container with magnetic stirring to ensure that the solid particle solution is uniformly suspended during the displacement process.
2.1.3. Determination of experimental injection rate. According to the plane radial flow production formula, simplify the calculation of seepage velocity at any point in the formation as shown in formula (1):

\[
v = \frac{Q}{2\pi h} \cdot \frac{1}{r}
\]  

Where \( Q \) is liquid production, \( h \) is oil layer thickness, and \( r \) is tubing radius.

It’s known that the liquid production is 200m³/d, the inner diameter of the tubing is 0.0762m, and the thickness of the oil layer is 52.6~60.0m. It’s found that the seepage velocity at the well wall is 0.97~1.10cm/min. And the flow rate corresponding to the core is \( v \times \pi r^2 = 4.75~5.41 \text{mL/min} \). Therefore, the reservoir was subjected to a reservoir damage experiment at a constant flow rate of 5 mL/min.

2.2. Experimental steps

Based on the test results of suspended solids content and particle size in the produced fluid, the steps for conducting an indoor reservoir damage assessment experiment are as follows:

a. The suspension solution is placed in an intermediate vessel, and the core is loaded into the core holder. b. The formation water is injected into the core at a constant rate, and calculates the initial liquid permeability \( k_i \) of the core. c. The suspension solution were used to displacement the core, and calculates the permeability \( k_1 \). d. Permeability \( k_{pv} \) are calculated after the end face cleaning of the core.

In order to quantitatively evaluate the damage of reservoirs with different content and particle size suspended solid particle solution, the permeability loss is calculated as follow.

\[
\alpha = \left(1 - \frac{k_{pv}}{k_i}\right) \times 100\%
\]  

The larger the value of \( \alpha \), the more severe the blockage. At present, the petroleum industry takes \( \alpha=30\% \) as the damage limit [8]. When \( \alpha>30\% \), it is considered that the blockage has formed damage.
3. Results and Discussion

3.1. Analysis of Suspended Solids Content and Particle Size in Production Fluid
The membrane filtration method was used to test the average suspended solids content of the produced liquid in Shengli Oilfield was 32 mg/L. The Malvern Nano ZS90 laser particle size analyzer was used to quantitatively analyze the uniform distribution of solid particles in the produced liquid, which was concentrated between 3.58μm and 4.20μm.

3.2. Analysis of Reservoir Damage Caused by Suspended Solid Particles in Re-injection Water
Fig. 2 depicts the results of the final permeability loss for different permeability injected with different content and particle size of suspended solid particle solutions.

![Figure 2](image_url)  
**Figure 2.** Damage results of suspended solid particle solution for different permeability

According to Fig. 2, 1) the damage of the suspended solid particles to the core increases with the increase of the injected pore volume and finally reaches a stable value. 2) For the core with the same permeability level, when one factor is fixed, the damage of the reservoir increase with the increase of the solids content and suspended particles. 3) Under the same experimental conditions, greater initially permeability means smaller permeability loss.

It can be seen from Fig. 2 that for a reservoir of 500–1000×10^{-3}μm² permeability, the suspended content is less than 10mg/L, the particle size is less than 6.5μm, and the permeability loss is less than 30%(as shown by the dotted line). For the 1000–2000×10^{-3}μm² permeability reservoir, when the suspended solid particle solution content is less than 30 mg/L, the particle size is less than 8.8μm, and then the permeability loss is less than 30%. Compared with the standard SY/T 5329-12, while satisfying the damage requirements, the content and particle size index has been relaxed and economic optimization has been achieved.

3.3. Analysis of Reservoir Damage Caused by Different Injection Rates
Considering the permeability of main layer of Shengli Oilfield, core with permeability of 1000×10^{-3}μm² has been taken as an example to study the impacts of different injection rates(0.5, 2.5 and 5mL/min)of suspended solid particles on the formation damage via changing the particle contents(10, 30mg/mL), specifically for the particles with size of 8.8μm. The effect of different injection rates on reservoir damage caused by suspended solid particles is shown in Fig. 3.
Figure 3. Effect of different injection rates on reservoir damage caused by suspended solid particle.

According to Fig.3, when the contents were 10mg/L and 30mg/L, the final permeability loss at low flow rate (0.5mL/min) was 9.5% and 6.7% higher than the high flow rate (5mL/min), respectively. It is indicated that the injection rate of the suspended solid particle has little effect on the damage of the core. Experimental analysis, for the same content, the permeability loss at a low flow rate is slightly larger. According to the analysis, the smaller the injection rate, the smaller the number of solid particles added in the core per unit time. On the one hand, the solid particles entering the core have enough time to be distributed around the large pores and contact. The continued injection of solid particles will cause the particles sealed at the large channels to be compacted [14]. On the other hand, effective sealing at the large channels will continue, and the continued injection of solid particles will cause the flow to divert. After the solid particles are plugged in these areas, other unsprayed areas are further activated. The reasons for these two aspects also make the solid particles retained in the core more, and the permeability damage is greater.

3.4. Injection plates of suspended solid particles with different permeability
The damage experiment results of suspended solid particles on different permeability were introduced into the sufer software, and through the interpolation of the minimum curvature method, the injection plate of the suspension solid particle solution with different contents and particle sizes for different permeability reservoirs can be obtained. As shown in Fig. 4(The red data in the figure is the contour of the permeability loss, and the blue data is the permeability loss obtained from experiment).

In the Fig. 4, it is assumed that the solid particle size in the produced fluid is 6.5μm and the solid particle content is 10mg/L. From the plate (a), it can be found that to the permeability is 500×10⁻³μm², the permeability loss of the reservoir is between 25% and 30%. From the plate (b), the permeability loss to the permeability of 1000×10⁻³μm² is between 20% and 25%, and so on. Or the gas permeability of the reservoir is known, and the production fluid containing the solid particles is injected into the reservoir. If the permeability loss is controlled to be less than 30%, the range of solid particle sizes and contents below the damage is found in the injection plates.
4. Conclusion

(1) The average content of suspended solid particles in the production fluid of Shengli Oilfield is 32mg/L, and the particle size distribution of suspended solid particles is evenly distributed, which is concentrated between 3.58μm–4.20μm.

(2) The damage of the suspended solid particles to the core increases with the increase of the injected pore volume and finally reaches a stable value. For the core with the same permeability level, when the particle size of the suspended solid is fixed, the damage of the reservoir increase with the increase of the solids concentration. When the concentration of suspended particles is certain, larger the particle size will cause greater ultimate damage to the core. Under the same experimental conditions, greater initially permeability means smaller permeability loss.

(3) When other conditions are the same, the slower the injection rate, the greater the damage of the suspended solid particle solution will cause to the core, but the overall effect is not obvious.

(4) According to the experimental results, the injection limit suitable for the suspended solid particle solution of Shengli Oilfield is obtained. For the 500×10^{-3}μm² permeability reservoir, the suspended solid particle content is less than 10mg/L, and the particle size is less than 6.5μm. For 1000×10^{-3}μm² permeability reservoir, the suspended solid particle content is less than 30mg/L, and the particle size is less than 8.8μm. And obtained suspension solid particle solution injection plate.
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