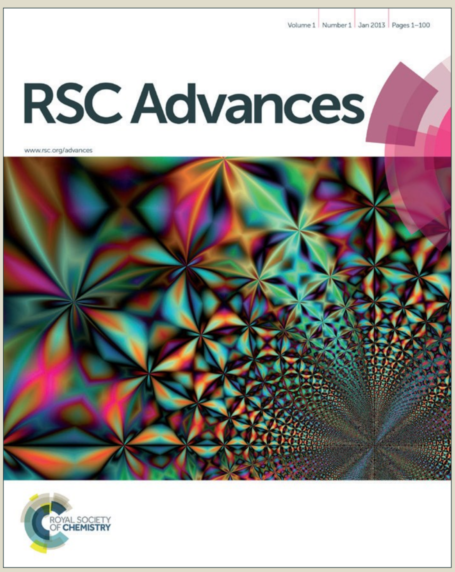
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Application and Experimental Study of Cyclic Foam Stimulation

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Abstract: Formation damage is a serious problem in the oil and gas industry. Based on the common reservoir damage, its damage conditions and factors are summarized in four categories in this paper. Worldwide advanced technologies applied in reservoir damage treatment are reviewed. For the first time, we propose a concept of injecting nitrogen foam into a formation to treat its damage from sand blocking. An application of Cyclic Foam Stimulation is introduced, which enhances well productivity significantly. An experiment apparatus of Cyclic Foam Stimulation is designed. It includes a wellbore vessel that can stimulate an effect of sand setting. A reservoir vessel is designed to supply foam. Additionally, in order to simulate the formation damage caused by the size and distribution of fine sands, six pieces of artificial cores, which are porosity contrastive and sand producible, are prepared based on the technology of pressure control and PVA membrane wrapping. The experimental results show that foam has a good discharge effect on sand blocking. Moreover, an effect of the size and distribution of fine sand on porosity is studied. The smaller the size of grain and the more uniform the grain distribution, the worse the formation porosity. A porosity recovery factor has been defined. The recovery rate of porosity is also studied. A scientific guide for the application of Cyclic Foam Stimulation can be generated from the studies in the paper.

Keywords: Formation damage; porous media; foam; plugging treatment; porosity

1. Introduction

Formation damage is a serious problem in the oil and gas industry.[1] Formation damage may occur in every production process during oil and gas production.[2]

Formation damage is usually hard to notice, which causes a great reduction in production.[3] It is triggered by a variety of factors, including: drilling, production, hydraulic fracturing and workover processes.[2] Formation damaged will lead to a permeability decrease, a skin factor increase and a production index decrease. Formation damage cannot be reversible usually. Generally, the material in porous media is not displaced spontaneously. This phenomenon is known as a reverse funnel effect.[4]

A lot of efforts have been devoted to finding effective ways to treat formation damage. Traditional formation damage repairing methods include matrix stimulation and hydraulic fracturing, which have received some success in field applications. However, they come along with many limitations at the same time. A fluid (usually acid) used in matrix stimulation can cause equipment/tubing corrosion, the secondary reservoir damage as well as pollution of the environment. Hydraulic fracturing construction costs huge amounts of time and capitals. In addition, these two methods have specific requirements to be used, which limit their applications. Furthermore, they are not easily applied to horizontal wells, especially the matrix stimulation.[5]

Foam is used to enhance oil recovery in oil and gas fields.[6] Foam produced passes a stability test and the qualified foam can be used as a method to enhance oil recovery.[7-10] By reducing the mobility of gas and steam, nitrogen foam flooding and thermal foam flooding, respectively, are used in traditional oil reservoirs and heavy oil reservoirs.[11, 12] Foam can reduce the bottom water coning of thin reservoirs by use of a negative pressure near wellbore, which is called a foam inhibiting water cone technology.[13] Nitrogen foam mud drilling can be used to reduce fluid column pressure in wellbore, improve the drilling speed and reduce the pollution of a reservoir.[14] Foam flooding is one of the effective ways of improving oil recovery after water flooding. Its test results and practical applications have proved to be very effective.[15, 16] In this paper, the method that the foam is used to treat reservoir damage caused by sand plug is studied.

Nitrogen foam is a complicated system and a structured fluid. Bubbles with different sizes separated by lamellae form a foam fluid with a special structure. Under the shearing action, the foam can deform, collapse, coalesce, and regenerate, which eventually leads to complexity of foam transporting and blocking in porous media.[17] Therefore, an experimental study on an effect of Cyclic Foam Stimulation is required.

The experiment apparatus of Cyclic Foam Stimulation is designed. It includes a wellbore vessel that can simulate an effect of sand setting. A reservoir vessel is designed to supply foam. Six pieces of artificial cores, which are porosity contrastive and sand producible, are prepared based on the technology of pressure control and PVA membrane wrapping in order to simulate the formation damage caused by the size and distribution of fine sand. The results of Cyclic Foam Stimulation experiments show that foam has a good remedy effect on sand blocking. In addition, the effects of the size and distribution of fine sand on formation porosity are studied. A scientific guide for the application of Cyclic Foam Stimulation can be given from the studies in this paper.

2. Conditions and Factors of the Formation Damage

Under the condition of pore-fluid balance, minerals and solid particles are usually present on the pore surface in the form of adsorption. But conditions of the chemical, thermodynamical and mechanical change will lead to an equilibrium state transforming into a non-equilibrium state, changes of salinity and a rate, thermal shock phenomenon, and particle separation and precipitation. When the pore surface and fluid balance is broken by reservoir production and EOR practice, minerals may be dissolved in the water phase and generate a lot of different ions, and the particles on the pore surface may also be released into the liquid phase. Once these ions and particles move into the liquid phase, they can be moved.

The conditions and factors of formation damage can be divided into four categories[1]:

1) The type, shape and location of the original mineral, such as: a reservoir fluid and the characteristics of the matrix.

2) Composition of the original and external fluid: the invasion of the external fluid, such as water chemicals used to improve oil recovery, drilling mud invasion and workover fluid.

3) Temperature, pressure and characteristics of the original reservoir, such as a production system, well production, and wellbore pressure and temperature changes.

4) Development practices of the well and reservoir, such as: the process of drilling and completion, all kinds of processes of EOR and fracturing.

3. Measures of Formation Damage Remedy

A remedy measure is a method of treating reservoir damage by removing blockage or opening new channels from blocked areas. [18] Since all repairing measures need to be carried out through wells, a repairing process is also known as a breaking down process. Basic repairing processes are divided into the following three categories: 1) physical remedy; 2) chemical remedy; 3) combined physical and chemical remedy.

Some new repairing measures are

Heating remedy: using heat to remove reservoir damage caused by clay swelling and water blocking. [19]

Hydraulic vibration remedy: using a low frequency hydraulic vibration generator to load water, to make water form low frequency and high pressure water jet shock wave. [20]

Artificial earthquake remedy: sending electricity to the ground through a cable (usually the voltage is about 10 - 70 KV and the electricity is 10 - 25 KA) after the switch of capacitor discharge, pulse discharging in a well fluid to form pressure pulse in a reservoir. [21]

Ultrasonic remedy: putting an ultrasonic transducer into a reservoir with a cable; the generated ultrasonic wave make effects directly on the solid and liquid underground after turning on power, which forms the intense vibration wave near wellbore. [22]

4. Concept and Application of Cyclic Foam Stimulation

Cyclic Foam Stimulation is a physically unblocking technology due to the expansion and carrying abilities of foam. By injecting foam into a formation, it can improve the porosity and permeability of a near-wellbore region and enhance oil and gas well productivity. The process of Cyclic Foam Stimulation can be divided into five phases:

i. Discharging phase: The first phase injects foam to discharge a fluid in wellbore.

ii. Foam injection phase: The second phase injects foam to a formation through wellbore with certain foam quality and an injection rate to avoid sand plugging in deeper strata. The amount of required foam depends on the degree of formation damage. By injecting high-pressure foam to the formation, foam can extend to its pore throats and remove sand plugging.

iii. Soaking phase: The third phase is a soaking phase. Its objective is to let foam spread out throughout the formation.

iv. Foam production phase: The fourth phase produces foam. Foam can treat the formation damage by carrying sand into wellbore. The production phase is maintained until there is no foam.

v. Sand production phase: The final phase cycles foam to take sand out of wellbore.

Well-X in an oilfield under study is a heavy oil production well, which is chosen to apply Cyclic Foam Stimulation. The properties of Cyclic Foam Stimulation are demonstrated in Figure 1. Figure 2 indicates that the oil production rate before the Cyclic Foam Stimulation pilot project in Well X was 15~20 m^3/d. The well was shut in for 11 months due to sand plug. The oil rate in the first production period after soaking was 18 m^3/d and reached its peak production 80 m^3/d at the 67th production day. This showed that permeability and porosity are enhanced significantly.

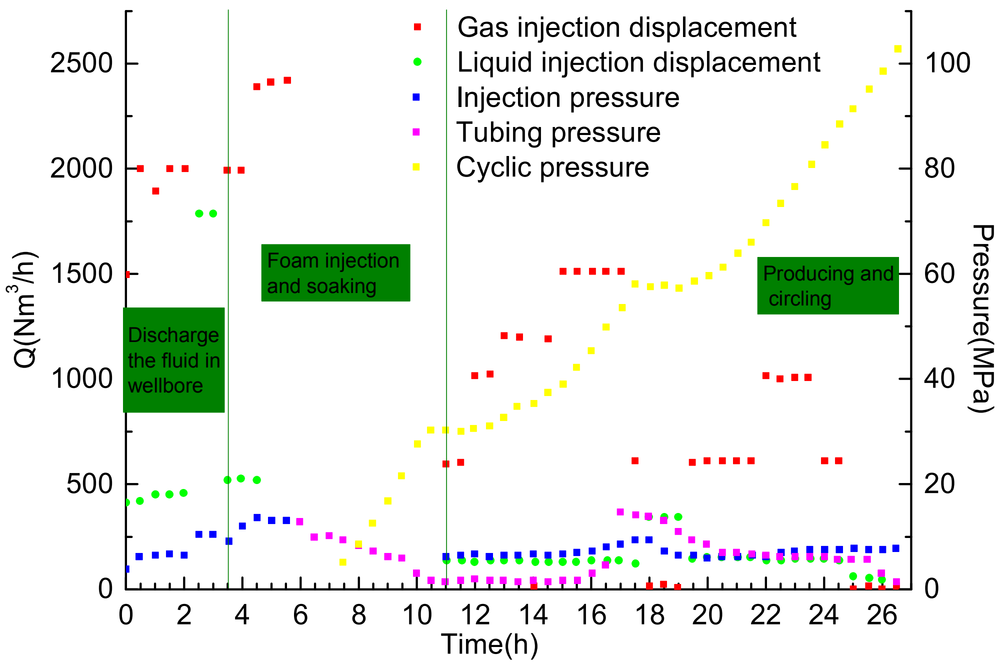

Figure 1. Properties of Cyclic Foam Stimulation operations

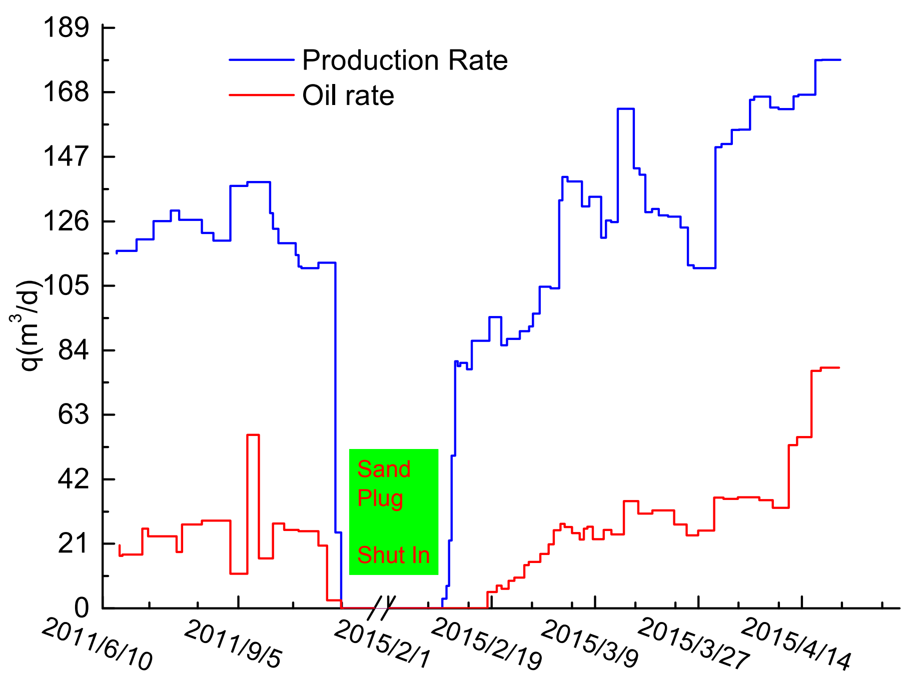

Figure 2. Well X production history after Cyclic Foam Stimulation

5. Experimental Section

5.1. Experimental Apparatus

A system of Cyclic Foam Stimulation experiments is developed at the China University of Petroleum (Beijing) and Haian Huayuan Company. The system consists of a foam injection part, a reservoir part, a wellbore part and a measurement part.

The foam injection part includes: a nitrogen bottle (supplying air), a high pressure vessel (depositing the foaming agent solution), a foam generator (mixing nitrogen and the foaming agent solution; revolving speed, 0-1000 r/min; volume, 5,000 mL; pressure, 20 MPa) and a high-pressure pump (injecting foam).

The reservoir part includes: a core holder (pressure, 30 MPa; temperature, 150℃; a screen is connected to one end of a reservoir vessel for preventing sand from entering the reservoir vessel), a core, a reservoir vessel (storing more foam; 38×300 mm； pressure, 20 MPa), and a back pressure pump (providing the surrounding pressure； pressure, 30 MPa).

The wellbore part includes: a wellbore vessel (a screen is loaded at the entry point for collecting sand which is carried into a wellbore vessel；pressure, 20 MPa) and two digital pressure gauges (on both ends of the wellbore vessel；precision, 0.25%; pressure, 40 MPa).

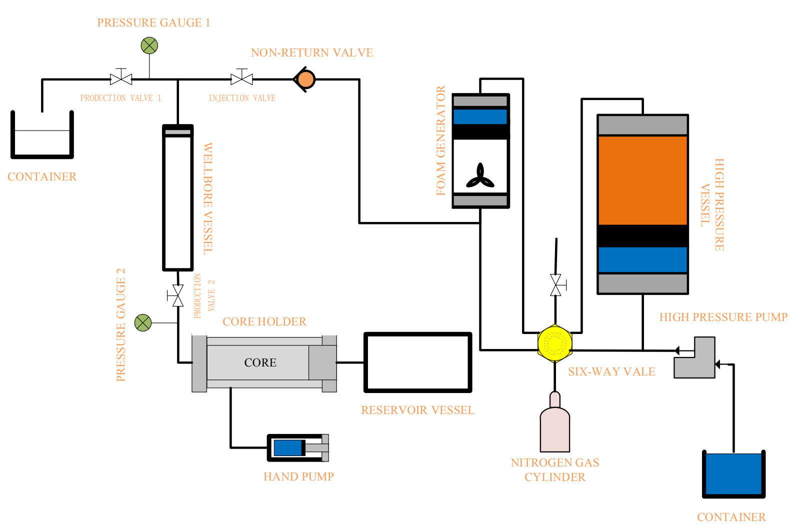

Figure 3. Experiment apparatus of Cyclic Foam Stimulation experiments.

5.2. Experimental Conditions

The purity of nitrogen gas is 99.99%.

The agent of petroleum sulfonate (PS) anionic surfactant concentration is 0.5%.

Cores

Because natural cores are not only rare and precious but also have poor repeatability, artificial cores are used in our experiments. Most of the sand production experiments use sand packs to simulate producible cores. However, the sand in the sand packs is not cemented and cannot reflect an actual reservoir accurately. This experiment uses sand producing artificial cores manufactured at the China University of Petroleum in Beijing to simulate an actual sand producing reservoir.

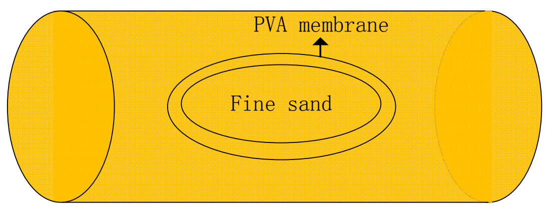

Figure 4. Schematic diagram of an artificial core.

The sand producing cores need to be put into a PVA dissolved solution for eight hours before use for degrading the PVA membrane and releasing the fine sand. After being saturated by formation water, they are dried at 80℃ constant temperature for 24 hours in a dryer. The physical properties of the cores are shown in Table 1.

Table 1. The physical properties of the cores

Core number	Height (cm)	Volume (cm^3)	Grain diameter (μm)	Ratio	Quantity (g)	Porosity (%)
B1	8.16	91.38	99	1	40	23.45
B2	8.23	93.63	124	1	40	24.17
B3	8.25	92.39	148	1	40	24.89
Y1	8.17	92.23	99：124：148	1:1:2	40	25.08
Y2	8.29	93.86	99：124：148	1:2:1	40	23.26
Y3	8.31	94.24	99：124：148	2:1:1	40	24.18

5.3. Experimental Procedures

The experimental procedure is composed of the following steps:

i. Test the initial porosity of a core and then put it in the core holder.
ii. Inject nitrogen gas at a certain pressure (P_1) into the foam generator by a six valve.
iii. Put the foaming agent into the high pressure vessel by using a high pressure pump and then inject the foaming agent at a certain pressure (P_2) into the foam generator.
iv. Open the magnetic stirring device in the foam generator for five minutes to make sure that the nitrogen gas and foaming agent mix uniformly in the foam generator.
v. Use the high pressure pump to inject the foam in the foam generator slowly into the wellbore vessel - core holder - reservoir vessel and record the pressure at the ends of the wellbore at the same time.
vi. Close the injection valve and keep the foam fully reacting in the core for a period of time.
vii. Open the production valve and discharge the foam rapidly.
viii. After a period of time, close the production valve, take out the sand in the wellbore vessel and dry it; then measure the quantity of the sand; dry the core and test its porosity after Cyclic Foam Stimulation; finally, put the core into the core holder and repeat steps vii and viii.

The gas-liquid ratio of foam

The nitrogen gas volume is V_h when injecting nitrogen gas into the foam generator at P_1 pressure. After injecting the foaming agent solution into the foam generator, pressure rises to P_2. At this time, the nitrogen gas volume in the foam generator is

$$V_1 = V_h \times P_1 / P_2 \qquad (1)$$

In this equation, V_h equals the volume of the foam generator. The volume of the foam agent solution is

$$V_L = V_h \times (1 - P_1 / P_2) \quad (2)$$

Thus the gas-liquid ratio is

$$\alpha = V_1 / V_L = \frac{P_1}{P_2 - P_1} \quad (3)$$

During the experiments, by controlling the nitrogen gas injection pressure P_1 in the foam generator and the foaming agent solution injection pressure P_2, we try to keep the same quality of foam in each experiment to eliminate the effect of foam quality on the experiments.

5.4. Experimental Results

We define the porosity recovery factor

$$\beta_\phi = (\phi_1 - \phi_0) / \phi_0 \quad (4)$$

where ϕ_0 is the initial porosity of the core and ϕ_1 is the core porosity after Cyclic Foam Stimulation. We also define the produced sand ratio

$$\varepsilon = m_1 / m_0 \quad (5)$$

where m_0 is the total quantity of fine sand and m_1 is the quantity of sand discharged by Cyclic Foam Stimulation.

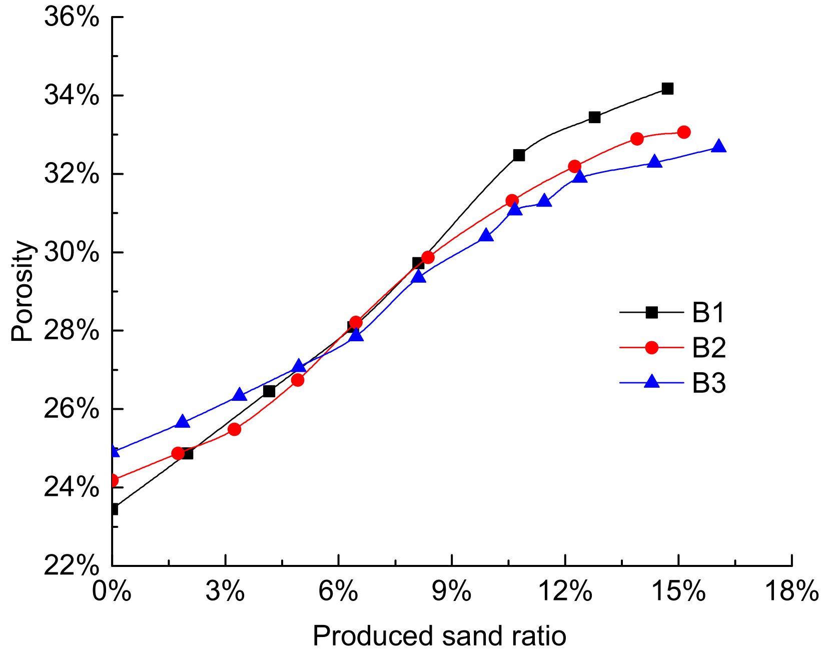

Figure 5. Porosity vs produced sand ratio

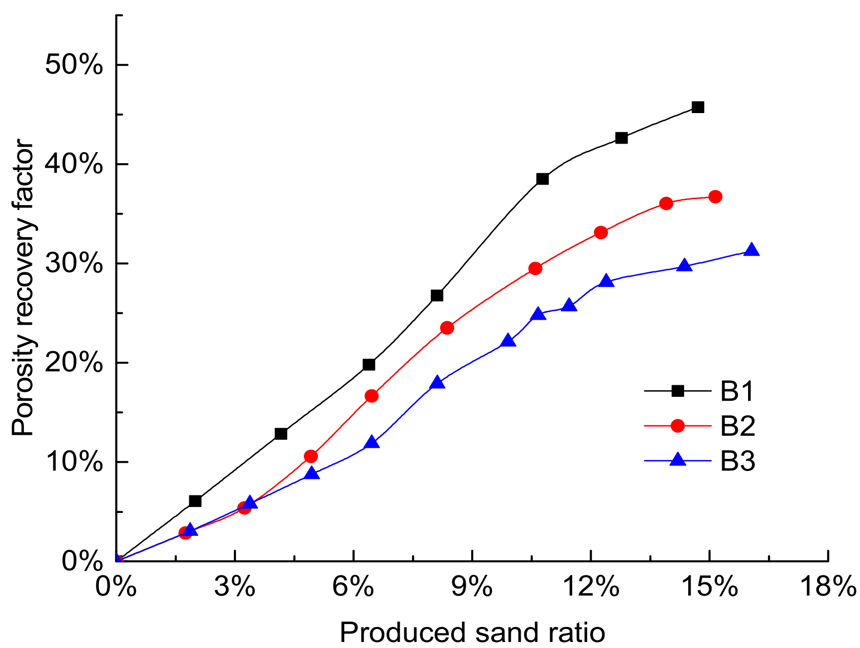

Figure 6. Porosity recovery factor vs produced sand ratio

The sizes of drifting sand filled in the cores of B1-3 are 99μm, 124μm and 148μm, respectively. The total quantity of fine sand is 40g. B1-3 are used to simulate formation damage by different sizes of particles. As shown in Figure 5, the primary porosity order of the B cores is B3, B2, and B1 from large to small. As the compaction pressures of B cores are all the same, the difference between B1-3 is due to the sizes of fine sand. It can be seen that the smaller the blocking particle size, the more obvious the porosity declines. When the produced sand ratio is between 2.5% and 5.8%, the porosity order of the B cores from large to small changes to: B3, B1, and B2. Combining with Figure 6, we can see that the B1 core recovery degree is far higher than that of B3 and B2. After Cyclic Foam Stimulation, the order of porosity from large to small is: B1, B2, and B3. In addition, we can see that the smaller size particles make more contribution to formation damage remediation than the bigger size particles do.

As shown in Figure 6, more blocked pores have been unblocked as the produced sand ratio becomes bigger. Moreover, the porosity recovery rate becomes slower when the produced sand ratio is larger.

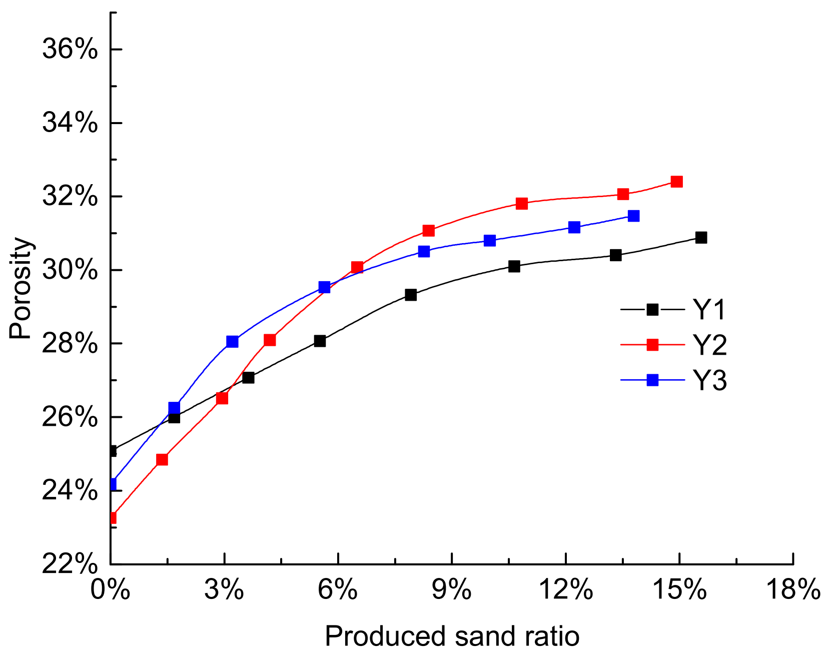

Figure 7. Porosity vs produced sand ratio

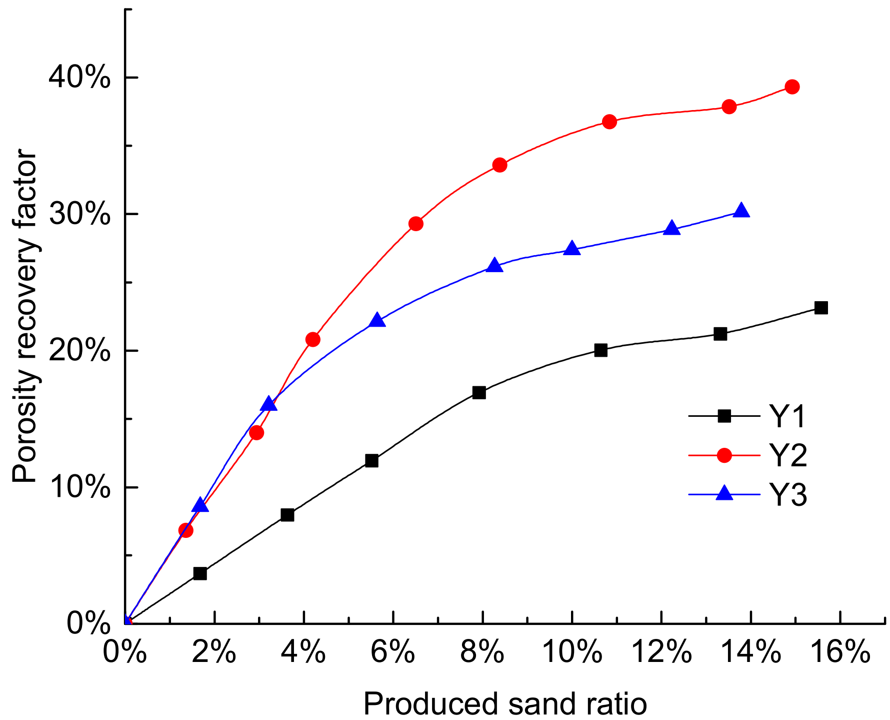

Figure 8. Porosity recovery factor vs produced sand ratio

Similarly, the quantity of fine sand filled in the Y1-3 cores is 40 g, but its fine sand ratio is different. The quantities of fine sand in the Y1 core, with a grain diameter of 99μm, 124μm and 148μm, are 10g, 10g and 20g, respectively. The Y2 core contains 20g drifting sand of 124μm and both 10g of 99μm and 148μm. The Y3 core contains 20g drifting sand of 99μm and both 10g of 124μm and 148μm. They are used to simulate the porosity damage degree according to different particle size distribution.

As shown in Figure 7, the porosity order before producing sand from large to small is: Y1, Y3, and Y2. Because the free sand particle size in the Y2 core is 124μm, the fine sand distribution in Y2 is more uniform than that in Y3 and Y1. According to the original porosity order, we can conclude that the more uniform the blocking particle size, the more serious the porosity damage. Since the blocking particles of different sizes can mix better and combine more tightly, it is more difficult for Y2 to have fluid inflow and outflow. When the produced sand ratio is more than 6%, the porosity order of Y from large to small is: Y2, Y3, and Y1. Therefore, the blocking of a uniform particle size distribution generates the most serious problem for formation porosity. The final porosity of the Y3 core is higher than that of the Y1 core. Because the size of most free sand particles of the Y3 core is 99 μm and the size of most free sand particles of the Y1 core is 148μm, we can see that the smaller size the blocking particles, the more damage the formation porosity.

Similarly, as shown in Figure 8, more blocked pores have been unblocked as the produced sand ratio becomes bigger. In addition, the porosity recovery rate becomes slower when the produced sand ratio is larger.

6. Discussions

Formation damage is a great challenge to the petroleum industry and leads to a decrease in porosity and porosity of a formation. There are a lot of efforts that have been devoted to finding effective methods to treat formation damage. Traditional formation repairing methods include matrix stimulation and hydraulic fracturing, which have received some success in field applications. However, they have some limitations, such as secondary damage, and are not suitable for horizontal wells.

In this paper, the damage conditions and factors of common reservoirs are summarized in four categories. According to sand plugging, sand particles tend to stay at three places of pores. Advanced technologies applied in reservoir damage remedy are introduced. After these reviews, we have developed a concept of injecting nitrogen foam into a formation to treat its damage from sand plugging for the first time. The results of a Cyclic Foam Stimulation application show that it enhances the well productivity significantly. The experiment apparatus of Cyclic Foam Stimulation has been designed. Additionally, in order to simulate the formation damage caused by the size distribution of fine sand, six pieces of artificial cores, which are sand producible, have been prepared based on the technology of pressure control and PVA membrane wrapping.

The experimental results show that foam has a good discharge effect on sand blockage. A scientific guide for an application of Cyclic Foam Stimulation can be provided with the method developed. As the effect of Cyclic Foam Stimulation is due to the quality of foam, it is necessary to do more systematical research on it.

7. Conclusions

Based on the damage conditions and factors, a concept of injecting nitrogen foam into a formation to treat its damage from sand plugging has been proposed for the first time, which can enhance both the porosity and the permeability of the formation significantly. In addition, an application of Cyclic Foam Stimulation is introduced. The experiment apparatus of Cyclic Foam Stimulation has been designed. Furthermore, in order to simulate the formation damage caused by the size and distribution of fine sand, six pieces of artificial cores, which are sand producible, have been manufactured based on the technology of pressure control and PVA membrane wrapped.

The experimental results show that foam has a good discharge effect on sand blockage and reveal some relationships about the size and distribution of free sand vs formation porosity. Moreover, a porosity recovery factor has been defined. Some guidelines on porosity recovery have been given.

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Notes

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