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Application and experimental study of Cyclic Foam Stimulation

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

1. Introduction

Formation damage is a serious problem in the oil and gas industries.[1] Formation damage may occur in every production process during oil and gas production.[2] Formation damage is usually hard to notice and can therefore cause a great reduction in productivity.[3] It is triggered by a variety of factors, including drilling, production, hydraulic fracturing and workover processes.[2] Formation damage leads to a permeability decrease, skin factor increase and production index decrease. Formation damage cannot usually be reversed. Generally, material deposited on porous media cannot be displaced spontaneously. This phenomenon is known as the reverse funnel effect.[4]

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

Foam is used to enhance oil recovery in oil and gas fields.[6] The foam used must pass a stability test before 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 bottom water coning in thin reservoirs by the use of negative pressure near the wellbore, which is called foam inhibited anti-water coning technology.[13] Nitrogen foam mud drilling can be used to reduce fluid column pressure in a wellbore, improve the drilling speed and reduce the pollution of a reservoir.[14] Foam flooding is one of the effective ways to improve oil recovery after water flooding, test results and practical applications have proved the method to be very effective.[15,16] In this paper, a foam method is used to treat the reservoir damage caused by sand plugging.

Nitrogen foam is a complicated system and a structured fluid. Bubbles with different sizes, which are separated by

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lamellae, form a foam fluid with a special structure. Under the shearing action, a foam can deform, collapse, coalesce and regenerate, which can eventually lead to the complications of foam transport and blocking in porous media.[17] Therefore, an experimental study on the effects of Cyclic Foam Stimulation is required.

Experimental apparatus for Cyclic Foam Stimulation was designed, which includes a wellbore vessel that can simulate the effect of sand setting. A reservoir vessel was also designed to supply the foam. Six artificial cores, which were porosity contrastive and sand producing, were prepared based on the technologies of pressure control and PVA membrane wrapping, in order to simulate formation damage caused by the size and distribution of fine sand. The results from the Cyclic Foam Stimulation experiments show that foam has a good remedying effect on sand blocking. In addition, the effects of the size and distribution of fine sand on the formation porosity were studied. A scientific guide for the application of Cyclic Foam Stimulation can be generated from the studies in this paper.

2. Conditions and factors resulting in formation damage

Considering the condition of pore-fluid balance, minerals and solid particles are usually present on the pore surface due to adsorption. However, changes in the chemical, thermodynamical and mechanical conditions can lead to an equilibrium state transforming into a non-equilibrium state, changes in salinity and rate, thermal shock phenomena and particle separation and precipitation. When the pore surface and fluid balance are broken by reservoir production and EOR practices, minerals may become dissolved in the water phase and generate a lot of different ions. Particles on the pore surface may also be released into the liquid phase. Once these ions and particles enter the liquid phase, they can be moved.

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

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

(2) The composition of the original and external fluids: the invasion of external fluid, such as water chemicals used to improve oil recovery, drilled mud invasion and workover fluid.

(3) The temperature, pressure and characteristics of the original reservoir, such as: the production system, well production, wellbore pressure and temperature changes.

(4) The development practices of the well and reservoir, such as: the processes of drilling and completion, and all kinds of processes for EOR and fracturing.

3. Remedy measures for formation damage

A remedy measure is a method for treating reservoir damage by removing blockages 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 remedies; (2) chemical remedies and (3) combined physical and chemical remedies.

Some new repairing measures are:

(i) Heating remedies: using heat to remove the reservoir damage caused by clay swelling and water blocking.[19]

(ii) Hydraulic vibration remedies: using low frequency hydraulic vibration generators to load water, which makes the water form low frequency and high pressure water jet shock waves.[20]

(iii) Artificial earthquake remedies: 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 switching of capacitor discharge, which discharges a pulse in the well fluid, forming a pressure pulse in the reservoir.[21]

(iv) Ultrasonic remedies: putting an ultrasonic transducer into a reservoir with a cable, the generated ultrasonic waves have direct effects on the solid and liquid underground after the power is turned on, which forms an intense vibration wave near the wellbore.[22]

4. Concept and application of Cyclic Foam Stimulation

Cyclic Foam Stimulation is a physical unblocking technology due to the expansion and carrying abilities of foam. Injecting foam into a formation can improve the porosity and permeability of the 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 fluid into the wellbore.

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

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

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

(v) Sand production phase: the final phase cycles foam to take sand out of the wellbore.

Well-X was the oilfield under study herein and it is a heavy oil production well, which was chosen for the application of Cyclic Foam Stimulation. The phase properties of Cyclic Foam Stimulation are demonstrated in Fig. 1. Fig. 2 indicates that the oil production rate before the Cyclic Foam Stimulation pilot project in Well X was 15–20 $m^3\ d^{-1}$. The well was shut for 11 months due to sand plugging. The oil rate in the first production period after soaking was 18 $m^3\ d^{-1}$ and reached its peak production of

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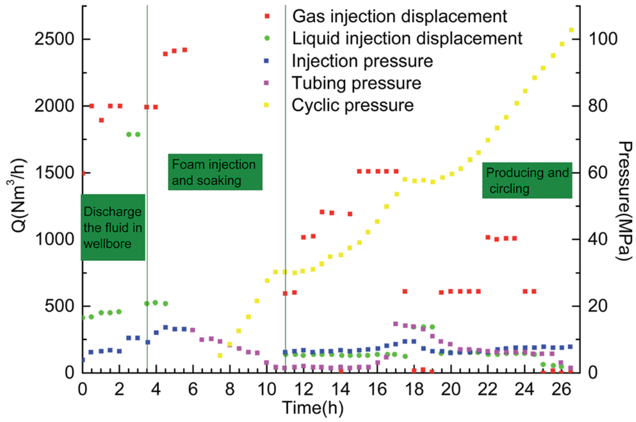

Fig. 1 The properties of the Cyclic Foam Stimulation phases.

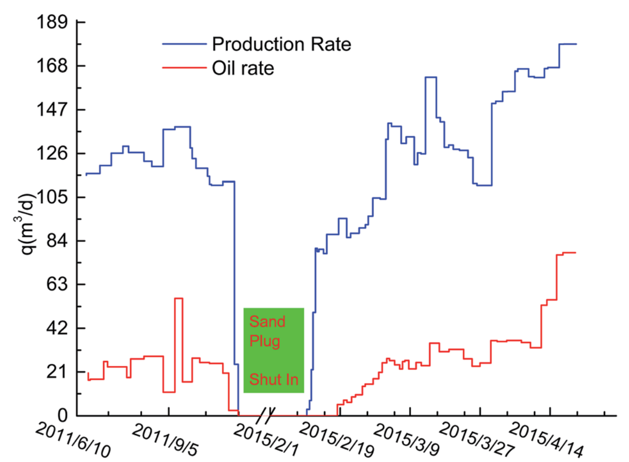

Fig. 2 Well-X production history after Cyclic Foam Stimulation.

80 m^3 d^{-1} on the 67th production day. This showed that permeability and porosity were enhanced significantly.

5. Experimental section

5.1. Experimental apparatus

The system for the Cyclic Foam Stimulation experiments was developed at the China University of Petroleum (Beijing) and Haian Huayuan Company. The system consisted of a foam injection part, a reservoir part, a wellbore part and a measurement part (Fig. 3).

The foam injection part included: a nitrogen bottle (for supplying air), a high pressure vessel (for depositing the foaming agent solution), a foam generator (for mixing nitrogen and the foaming agent solution; revolving speed, 0–1000 rpm; volume, 5000 mL; pressure, 20 MPa) and a high-pressure pump (for injecting the foam).

The reservoir part included: a core holder (pressure, 30 MPa; temperature, 150 °C; a screen was connected to one end of the reservoir vessel to prevent 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 included: a wellbore vessel (a screen was loaded at the entry point for collecting sand which was carried into the wellbore vessel; pressure, 20 MPa) and two digital pressure gauges (on both ends of the wellbore vessel; precision, 0.25%; pressure, 40 MPa).

5.2. Experimental conditions

The purity of the nitrogen gas was 99.99%. The petroleum sulfonate (PS) anionic surfactant agent concentration was 0.5%.

Cores. As natural cores are not only rare and precious, but also have poor repeatability, artificial cores were used in our experiments (Fig. 4). Most of the sand production experiments used sand packs to simulate producible cores. However, the sand in the sand packs was not cemented and could not reflect an actual reservoir accurately. These experiments used sand producing artificial cores manufactured at the China University of Petroleum in Beijing to simulate an actual sand producing reservoir.

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

5.3. Experimental procedure

The experimental procedure was composed of the following steps:

(i) The initial porosity of a core was tested and then it was put into the core holder.

(ii) Nitrogen gas was injected at a certain pressure (P_1) into the foam generator using six valves.

(iii) The foaming agent was put into the high pressure vessel using a high pressure pump and then the foaming agent was injected at a certain pressure (P_2) into the foam generator.

(iv) The magnetic stirring device in the foam generator was operated for five minutes to make sure that the nitrogen gas and foaming agent mixed uniformly in the foam generator.

(v) The high pressure pump was used to inject the foam in the foam generator slowly into the wellbore vessel–core holder–reservoir vessel and the pressures at the ends of the wellbore were recorded at the same time.

(vi) The injection valve was closed to keep the foam fully reacting in the core for a period of time.

(vii) The production valve was opened and the foam was rapidly discharged.

(viii) After a period of time, the production valve was closed. The sand in the wellbore vessel was taken out and dried; then the quantity of sand was measured. The core was dried and its porosity after Cyclic Foam Stimulation was tested; finally, the core was put into the core holder and steps (vii) and (viii) were repeated.

The gas–liquid ratio of foam. The nitrogen gas volume is V_h when injecting nitrogen gas into the foam generator at P_1

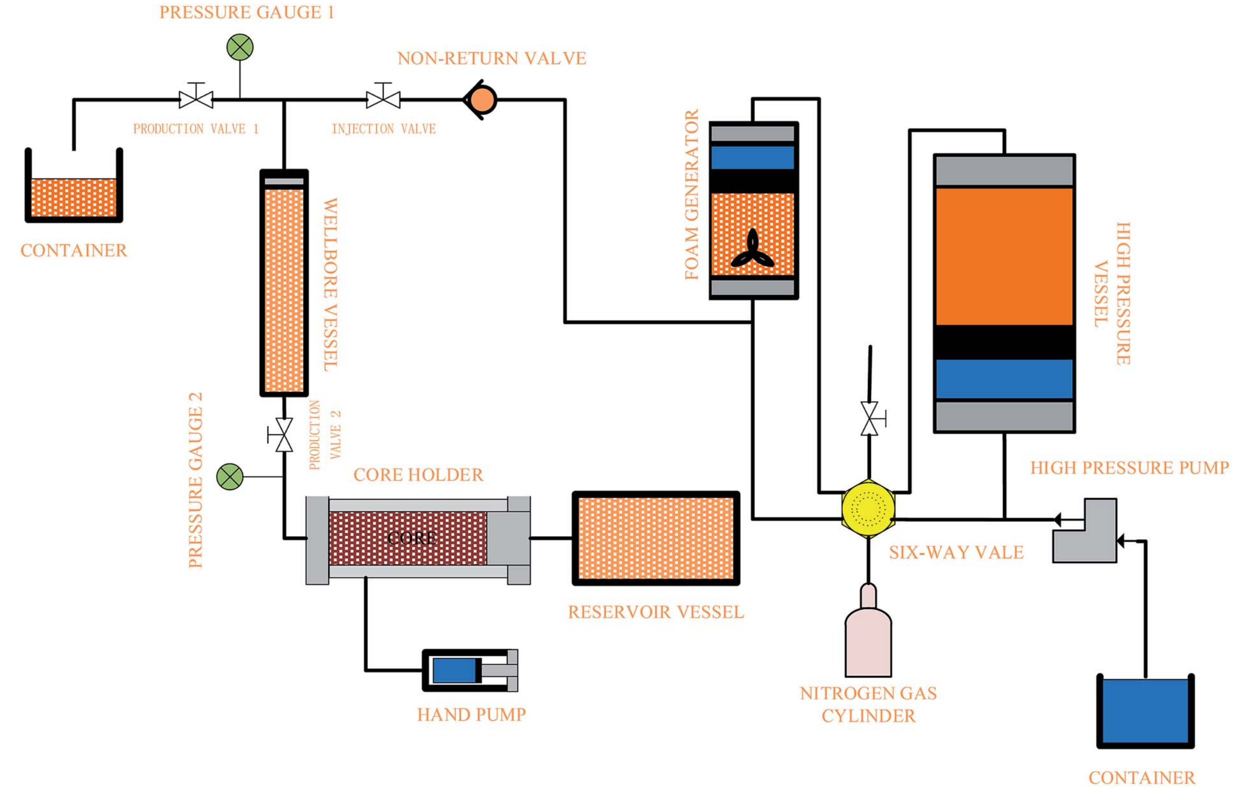

Fig. 3 Experimental apparatus for the Cyclic Foam Stimulation experiments.

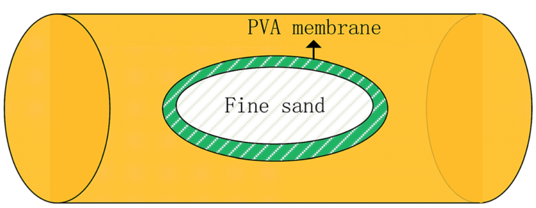

Fig. 4 Schematic diagram of an artificial core.

pressure. After injecting the foaming agent solution into the foam generator, the pressure rises to P_2. At this time, the nitrogen gas volume in the foam generator is:

$$V_1 = V_h \times P_1/P_2 \tag{1}$$

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

$$V_L = V_h \times (1 - P_1/P_2) \tag{2}$$

Thus the gas–liquid ratio is:

$$\alpha = V_1/V_L = \frac{P_1}{P_2 - P_1} \tag{3}$$

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 tried 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 as:

$$\beta_\Phi = (\Phi_1 - \Phi_0)/\Phi_0 \tag{4}$$

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

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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 as:

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

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

The sizes of the drifting sand filling the cores of B1–3 were 99 μm, 124 μm and 148 μm, respectively. The total quantity of fine sand was 40 g. B1–3 were used to simulate formation damage from different sizes of particles. As shown in Fig. 5, the initial porosity order of the B cores was B3, B2 and B1 from large to small. As the compaction pressures of the B cores were all the same, the differences between B1–3 were due to the size of the fine sand. It can be seen that the smaller the blocking particle size, the more obviously the porosity declines. When the produced sand ratio was between 2.5% and 5.8%, the porosity order of the B cores from large to small changed to: B3, B1 and B2. In combination with Fig. 6, we can see that the B1 core recovery degree was far higher than those of B3 and B2. After Cyclic Foam Stimulation, the order of porosity from large to small was: B1, B2 and B3. In addition, we can see that the smaller sized particles make more of a contribution to formation damage remediation than the bigger sized particles do.

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

Similarly, the quantity of fine sand filled in the Y1–3 cores was 40 g, but their fine sand ratios were different. The quantities of fine sand in the Y1 core, with grain diameters of 99 μm, 124 μm and 148 μm, were 10 g, 10 g and 20 g, respectively. The Y2 core contained 20 g of drifting sand of 124 μm diameter and 10 g of both 99 μm and 148 μm diameter grains. The Y3 core contained 20 g of drifting sand of 99 μm diameter and 10 g of both 124 μm and 148 μm diameter grains. They were used to simulate the porosity damage degree according to different particle size distributions.

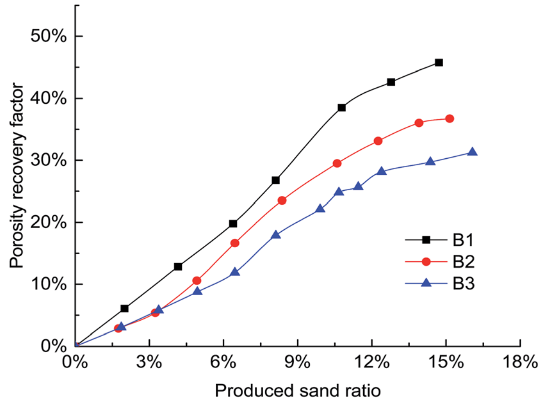

Fig. 6 Porosity recovery factor *vs.* produced sand ratio.

As shown in Fig. 7, the porosity order before producing the sand from large to small was: Y1, Y3 and Y2. As the free sand particle size in the Y2 core was 124 μm, the fine sand distribution in Y2 was 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 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 was more than 6%, the porosity order of Y from large to small was: Y2, Y3 and Y1. Therefore, the blocking caused by sand with a uniform particle size distribution generates the most serious problem in terms of formation porosity. The final porosity of the Y3 core was higher than that of the Y1 core. As the size of most of the free sand particles within the Y3 core was 99 μm and the size of most of the free sand particles within the Y1 core was 148 μm, we can see that the smaller the size of the blocking particles, the more damage there is to the formation porosity.

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

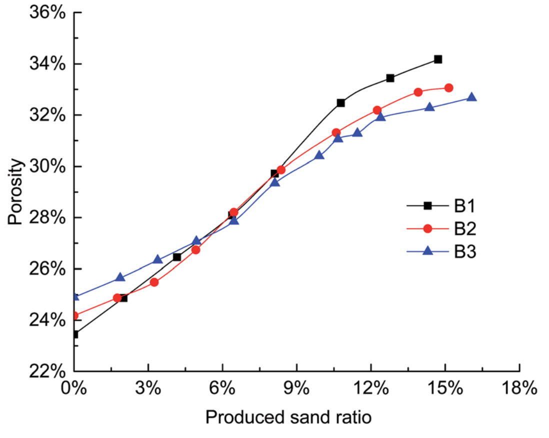

Fig. 5 Porosity *vs.* produced sand ratio.

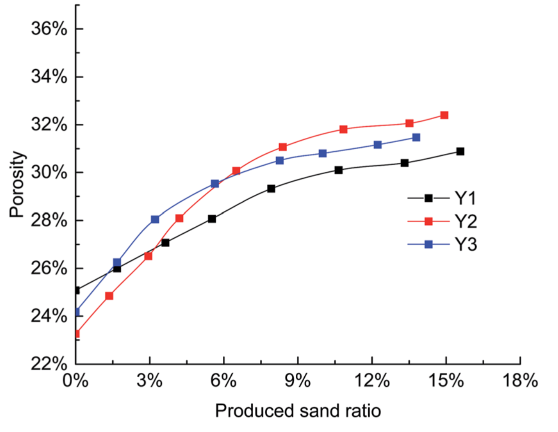

Fig. 7 Porosity *vs.* produced sand ratio.

6. Discussions

Formation damage is a great challenge for the petroleum industry and leads to decreases in the porosity and permeability of a formation. A lot of efforts have been devoted to finding effective methods for treating formation damage. Traditional formation repairing methods include matrix stimulation and hydraulic fracturing, which have shown 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 affecting common reservoirs were summarized into four categories. According to sand plugging, sand particles tend to stay in three areas of the pores. Advanced technologies applied as reservoir damage remedies have already been introduced. After this review, we developed the 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. Experimental apparatus for Cyclic Foam Stimulation has been designed. Additionally, in order to simulate the formation damage caused by the size distribution of fine sand, six artificial cores, which were sand producing, were prepared based on the technologies of pressure control and PVA membrane wrapping.

The experimental results show that foam has a good discharging effect on sand blockages. A scientific guide for the application of Cyclic Foam Stimulation can be generated from the method developed. As the effects of Cyclic Foam Stimulation are due to the quality of foam, it is necessary to do more systematic research on it.

7. Conclusions

Based on the damage conditions and factors, the 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 was introduced. Experimental apparatus for Cyclic Foam Stimulation has been designed. Furthermore, in order to simulate the formation damage caused by the size and distribution of fine sand, six artificial cores, which are sand producing, have been manufactured based on the technologies of pressure control and PVA membrane wrapping.

The experimental results show that foam has a good discharging effect on sand blockages and reveals some relationships between the size and distribution of free sand *vs.* the formation porosity. Moreover, a porosity recovery factor has been defined. Some guidelines on porosity recovery have been given.

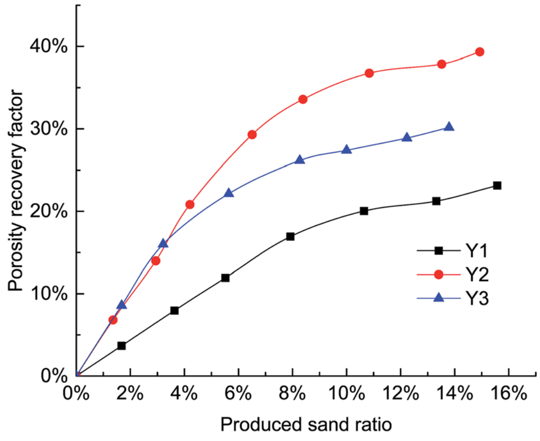

Fig. 8 Porosity recovery factor *vs.* produced sand ratio.

Conflict of interest

The authors declare no competing financial interest.

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