coatings

Article

Study on Stable Loose Sandstone Reservoir and Corresponding Acidizing Technology

Wei Song [1], Kun Zhang [2], Daqiang Feng [3], Qi Jiang [3], Hai Lin [3], Li Liao [3], Ruixin Kang [3], Baoming Ou [3], Jing Du [3], Yan Wang [4] and Erdong Yao [2,*]

1 Qinghai Oilfield Company, Qinghai 817500, China; songweiqh@petrochina.com.cn
2 State Key Laboratory of Petroleum Resources and Prospecting, China University of Petroleum, Beijing 102249, China; kun_123@foxmail.com
3 Drilling and Production Technology Research Institute, Qinghai Oilfield Company, Qinghai 817500, China; fdqqh@petrochina.com.cn (D.F.); jiangqiqh@petrochina.com.cn (Q.J.); linhaiqh@petrochina.com.cn (H.L.); liaoliqh@petrochina.com.cn (L.L.); kangruixingh@petrochina.com.cn (R.K.); oubmzcqh@petrochina.com.cn (B.O.); djqh@petrochina.com.cn (J.D.)
4 Institute of Logging Geology, Qinghai Oilfield Company, Qinghai 817500, China; wyanqh@petrochina.com.cn
* Correspondence: yaoed@cup.edu.cn

Abstract: The Sebei gas field is in the Sanhu depression area of the Qaidam Basin, which is the main gas-producing area and a key profit pillar for the Qinghai oilfield. The Sebei gas field within the Qinghai oilfield is characterized by high mud content, poor lithology, interflow between gas and water layers, and a propensity for sand production. The reservoir rocks are predominantly argillaceous siltstone with primarily argillaceous cement. These rocks are loose and tend to produce sand, which can lead to blockage. During its development, the Sebei gas field exhibited significant issues with scale formation and sand production in gas wells. Conventional acidization technologies have proven to be slow acting and may even result in adverse effects. These methods can cause loose sandstone to disperse, exacerbating sand production. Therefore, it is necessary to elucidate the mechanisms of wellbore plugging and to develop an acidizing system for plug removal that is tailored to unconsolidated sandstone reservoirs. Such a system should not only alleviate gas well plugging damage but also maintain reservoir stability and ensure efficient and sustained stimulation from acidization treatments. In this paper, the stability of unconsolidated sandstone reservoirs and the acid dissolution plugging system, along with the technological methods for stabilizing sand bodies, are studied through mineral component analysis, acid dissolution experiments, core immersion experiments, and other laboratory tests. The principle of synergistic effects between different acids is applied to achieve "high-efficiency scale dissolution and low sandstone dissolution". Three key indicators of dispersion, sand dissolution rate, and scale dissolution rate were created. The acid plugging solution formula of "controlled dispersion and differentiated dissolution" was developed to address these indicators. Laboratory tests have shown that the sandstone is predominantly composed of quartz and clay minerals, with the latter mainly being illite. The primary constituent of the wellbore blockage scale sample is magnesium carbonate, which exhibits nearly 100% solubility in acid. By adding a stabilizer prior to acid corrosion, the core's corrosion can be effectively mitigated, particle dispersion and migration can be controlled, and the rock structure's stability can be maintained. Laboratory evaluations indicate that the scale dissolution rate is greater than or equal to 95%, the sand dissolution rate is below 25%, and the system achieves a differentiated corrosion effect without dispersion for 24 h. Field tests demonstrate that the new acid solution plugging removal system enhances average well production and reduces operational costs. The system effectively mitigates the challenges of substantial sand production and reservoir dispersion, thereby furnishing a theoretical foundation and practical direction for acid plugging treatments in unconsolidated sandstone gas fields.

Keywords: differential corrosion; reservoir stability; reservoir sand control; unconsolidated sandstone

Citation: Song, W.; Zhang, K.; Feng, D.; Jiang, Q.; Lin, H.; Liao, L.; Kang, R.; Ou, B.; Du, J.; Wang, Y.; et al. Study on Stable Loose Sandstone Reservoir and Corresponding Acidizing Technology. *Coatings* **2024**, *14*, 667. https://doi.org/10.3390/coatings14060667

Academic Editor: Valeria Vignali

Received: 11 March 2024
Revised: 22 April 2024
Accepted: 15 May 2024
Published: 24 May 2024

1. Introduction

The reservoir depth of Sebei gas field in Qinghai oilfield is 350~2100 m and features shallow burial, long span, many thin layers, and large area difference [1]. The geological map of Sebei gas field is shown in Figure 1 [2]. The average Young's modulus is 296.7 N/m^2, the average uniaxial compressive strength is 3.71 MPa [2], the strength is very low, and it is easy to cause damage. The predominant lithology of the reservoir consists of siltstone and argillaceous siltstone, characterized by a loose rock structure with a high content of argillaceous material. The primary constituent of the reservoir's cement is argillite, complemented by clay minerals such as illite and mixed layers of illite/smectite. This composition endows the reservoir with pronounced water sensitivity, rate sensitivity, and acid sensitivity. During the gas extraction process, fine-grained migratory minerals like illite, present within the porous sandstone, become detached from the rock matrix due to the erosive actions of gas and water [3]. These particles are then transported through the combined forces of air and water, eventually leading to the clogging of the near-wellbore environment and the wellbore itself [4]. In recent years, as the volume of water discharged from gas fields has risen, coupled with the reduction in formation pressure and the escalation of intervention measures, the reservoir's permeability has been adversely affected. This degradation in permeability stems from a combination of solid-phase blockages, liquid-phase intrusions, and the consequences of capillary action [5].

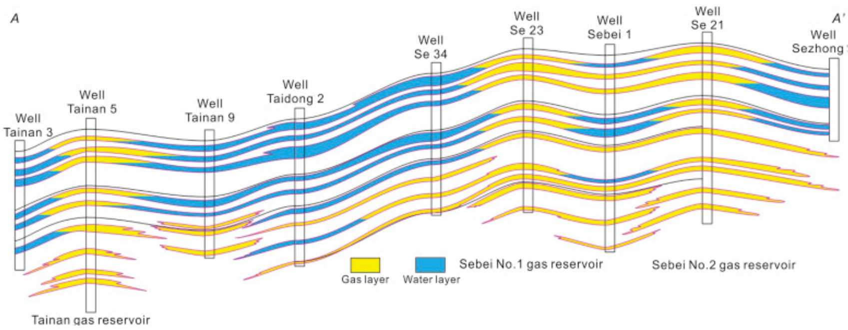


Figure 1. Geological map of Sebei gas field [2].

The main objective of sandstone matrix acidization is similar to that of a chemical breaker system; both involve the introduction of acid into the formation to dissolve and clear away pore-blocking materials within the oil and gas reservoir, thereby enhancing well productivity [6–8]. This process facilitates the unclogging of fluid conduits in the vicinity of the well, thereby rejuvenating and enhancing the productivity of oil and gas [9]. With the development of sandstone acidification at home and abroad for more than 100 years, the types of acidification technology are continuously enriched, various kinds of acid additives emerge endlessly, and the application range is more and more extensive [8]. Despite there being many applicable reservoir stimulation methods, acidizing technology can be considered one of the most effective methods in most fields where it has been applied, particularly when compared to other methods [10]. However, acidification will inevitably cause damage to reservoir rocks while removing blockage and restoring seepage capacity. The defects of loose sandstone, which is unconsolidated and easily produces sand, are further expanded in the acidification process. When the acid reacts with the blockage, it reacts with the clay minerals and the basement cement, which causes the loose rock to become more loose and the particle migration phenomenon to intensify [11,12]. Most of these particles will be discharged from the bottom of the well with the fluid, and some of them will settle in the wellbore under the action of gas and water, resulting in wellbore blockage, and a small part of the particles will migrate and accumulate in the throat connection, blocking the oil and gas seepage channels [13].

Historical analysis of post-acidization well performance in Sebei gas field indicates that, while acid removal initially led to a substantial increase in the output of previously clogged wells, this was accompanied by a significant release of mud particles from the wellhead [14]. Over time, this resulted in a gradual decline in productivity. Striking a balance between matrix acidization, which breaks down obstructions, and avoiding excessive rock disintegration is a critical issue in the acidization and stimulation of loose sandstone reservoirs. To address these challenges, a comprehensive approach was undertaken involving mineral composition analysis, ICP ion analysis, acid solution experiments, and core immersion tests, supplemented by field trials. The strategy leveraged the synergistic effects of various acids to achieve a principle of "high scale dissolution with minimal sand dissolution". Three pivotal indicators—dispersion, sand dissolution rate, and scale dissolution rate—were meticulously crafted, culminating in the development of an acid plugging solution formulated upon the principle of "controlled dispersion and differentiated dissolution". This innovation culminated in a comprehensive fluid system and procedural methodology aimed at stabilizing the sand body, offering an essential toolset for the effective acidization of unconsolidated sandstone gas fields.

2. Methodology

This section principally details the experimental methodologies employed. Initially, an in-depth analysis of the mineral components of rock and scale samples was conducted to ascertain their compositional elements, which laid the groundwork for the formulation of the acid system and reservoir stabilizers. Subsequently, acid dissolution trials were performed on the rock and scale specimens, leading to the identification of an acid solution with a "low sand dissolution and high scale dissolution" characteristic, followed by a refinement of its concentration ratio. The immersion experiment then ensued, wherein the rocks were submerged in the reservoir stabilizer to assess its efficacy in solidifying loose rock. The final phase involved conducting compatibility tests between the reservoir stabilizer and acid plugging solution, monitoring the impact of their application sequence on rock stability and acid corrosion, culminating in the selection of a robust sand body plugging solution system. The specific experimental process is shown in Figure 2.

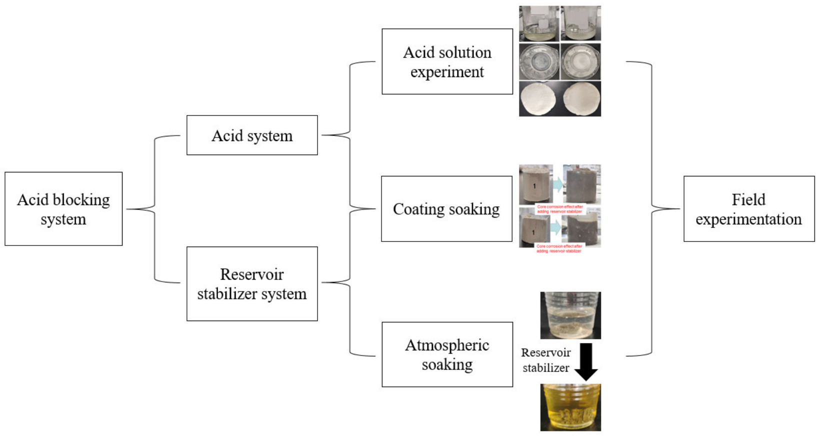


Figure 2. Flow chart of the experiment.

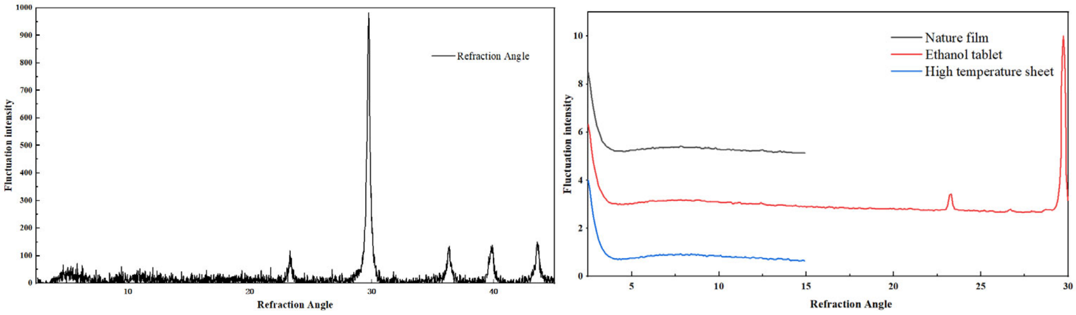
2.1. Reservoir Rock and Oil Pipe Scale

The reservoirs of Sebei gas field in Qinghai oilfield are mainly distributed in the Quaternary Sebei Formation (Q1) [2]. The buried depth of the gas layer is 350~2100 m. The porosity is mainly 26%~35%, with an average of 29%. The permeability ranges from 5 to 50 mD, with an average of 15 mD. The rock was taken from a well in the 1700 m reservoir of the Sebei Block (Figure 3a), which was drilled from an exploration well and processed into a small 1 cm^3 diameter rock and standard 2.5 cm diameter core. At the same time, a 1 m long oil pipe was intercepted and the internal scale sample was tested (Figure 3b); the oil pipe was taken from a blocked well in the same block. The rock and scale samples were analyzed by XRD.

(**a**) (**b**)

Figure 3. Reservoir rock and scale samples ((**a**): reservoir rock; (**b**): oil pipe scale).

The reservoir lithology of Sebei gas field is mainly argillaceous siltstone and argillaceous siltstone, with a small amount of fine sandstone. The average content of detritus is 69.7%, matrix 16.1%, and cement 14.2%. According to the analysis of sandstone mineral composition, quartz and clay minerals are mainly in the rock, followed by aragonite and hematite. Quartz accounted for 26.2%, clay minerals 25%, aragonite 12.7%, and hematite 13.4%. The clay minerals are dominated by illite, with an average of 68%. The mineral map is shown in Figure 4.



(**a**) (**b**)

Figure 4. XRD results of reservoir rock samples ((**a**): rock mineral analysis; (**b**): clay mineral analysis).

2.2. Acid Blocking System

2.2.1. Reservoir Stabilizer

The anti-swelling mechanism of inorganic salts is to reduce the thickness of the diffusion double layer and the Zeta potential of the clay surface [15]. Among them, potassium salt has the best anti-swelling effect and the most use, because the diameter of potassium ions (0.266 nm) matches the diameter of the void surrounded by six oxygen atoms (0.280 nm) on the clay surface, which makes it easy to enter this space and not easy to release from this space, which can effectively reduce the electronegative property of the clay surface. So our group chose KCl as an inorganic salt to prevent the clay from swelling [16].

According to XRD analysis, the main components are quartz and clay minerals, so the rock is mainly negatively charged, and once the water–rock reaction occurs, it will repel each other on the surface of the fine particles, leading to further dispersion of the rock. The mechanism of inorganic cationic polymer polyaluminum chloride (PAC) is to dissociate polynuclear hydroxyl bridge ions in water, which have a high positive electrovalence and a structure similar to clay and can be tightly adsorbed on the surface of fine particles, reducing the electronegativity of the surface of the particles [17].

As a stable colloid system, the nano-emulsion can form a new composite colloid system after adding the nano-emulsion to water, which can improve the stability and anti-expansion performance of rock blocks [18,19]. At the same time, the nano-emulsion can also change the wettability and slow down the dispersion of rock mass through the action of its surfactant. Dodecylpyridine chloride also acts as a surfactant, although it cannot prevent clay swelling, but it can still slow rock dispersion by changing rock wettability [20]. Therefore, our group compared these two surfactants to observe their anti-dispersion effects.

Our group mixed three types of agents and evaluated their rock stability through a series of tests.

2.2.2. Acid System

Six kinds of acids were selected for the test, namely hydrochloric acid, hydrofluoric acid, soil acid, solid acid (polycarboxylic acid), HEDP (organic phosphoric acid), and EDTA (amino polycarboxylic acid). Hydrochloric acid, hydrofluoric acid, and soil acid are strong acids and are the main acids for corrosion. The solid acid is a polycarboxylic acid, which can electrolyze a few H^+, and the acid can be maintained at a certain acidity during the dissolution process. HEDP is an organic phosphoric acid, which is not only a chelating agent but also has the effect of corrosion and scale inhibition, which can inhibit scale while dissolving scale. EDTA is an amino polycarboxylic acid, ethylenediamine tetraacetic acid, and an organic acid. It can dissolve the scale sample and form a complex with the metal, which can be used as an iron ion stabilizer. The final acid system formula was determined by comparing the dissolution effect of different acid solutions.

2.3. Experimental Method

2.3.1. Blockage Analysis—Acid Corrosion Test

The acid dissolution experiment is a commonly used geological experiment; its purpose is to understand the dissolution of different mineral components in the rock through the dissolution of acid samples and then reveal the composition and distribution of underground rock. The dissolution rate (%) is directly related to the acidification effect. By comparing the dissolution rate of different acid solutions to rock powder and scale samples, the final acid type and proportion can be determined. The evaluation method of the corrosion inhibitor refers to the static weight loss method specified in the Oil and Gas Industry Standard SY/T5405, [21] "performance test method and evaluation index of corrosion inhibitor for acidizing". The main steps are as follows: (1) Weigh the rock debris. A weight of m_1g (generally about 5 g, accurate to 0.0001 g) of the rock debris is placed in containers (conical bottles or glass beakers can be used when hydrochloric acid is dissolved, plastic beakers must be used when soil acid is dissolved). (2) Acid corrosion. Pour 50 mL of the required concentration of acid into a container, place the container in a 45 °C water bath for 120 min, and then take it out. (3) Weigh the filter paper. The filter paper in the dryer is numbered and weighed. The quality of the filter paper is m_2. (4) Filter. The liquid after the complete reaction is filtered. (5) Dry the remaining rock debris. The filtered residue and filter paper are baked to constant weight in the oven at 105 °C, then cooled and weighed in the dryer with the mass of m_3. (6) The experiment is repeated three times to obtain the average value and eliminate the error.

The formula for calculating the dissolution rate is as follows [21]:

$$\eta = \frac{m_1 + m_2 - m_3}{m_1} \quad (1)$$

η—Dissolution rate of rock sample, %;
m_1—Quality of rock sample before test, g;
m_2—Filter paper weight, g;
m_3—Quality of rock sample after test, g.

2.3.2. Rock Immersion Experiment at Room Temperature and Atmospheric Pressure to Evaluate Stabilizer and Acid

Experimental methods: 1 cm^3 rock blocks were used and the ratio of acid solution was 1:10. The block-loose sandstone was immersed into the reservoir stabilizer at normal temperature and pressure to carry out the immersion experiment, during which the influence of the system on maintaining the rock structure in water was evaluated.

Types of agents: ① Reservoir stabilizer: potassium chloride, polyaluminum chloride, Dodecylpyridinium chloride, and nano-emulsion; ② Acid solution: hydrochloric acid, hydrofluoric acid, mud acid, solid acid (polycarboxylic acid), HEDP (organic phosphoric acid), and EDTA (amino polycarboxylic acid).

The main basis of the reservoir stabilizer anti-dispersion system: (1) Clay anti-swelling: prevents clay expansion through clay stabilizer; (2) the use of agents to gather dispersed particles together: small cationic polymers or surfactants can gather dispersed particles together. Its schematic diagram is shown in Figure 5.

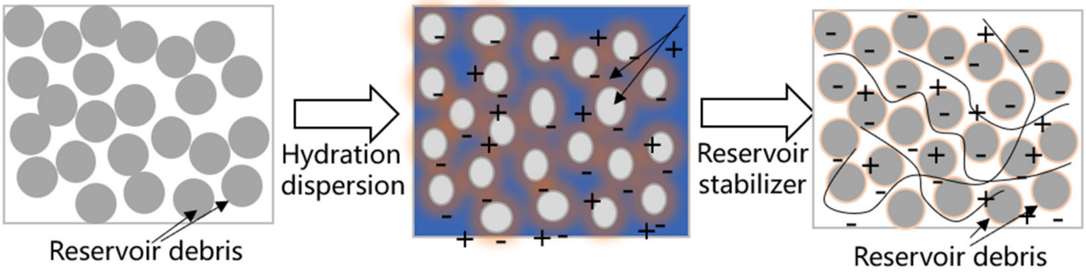


Figure 5. Schematic diagram of anti-dispersion principle of reservoir stabilizer.

Acidizing plugging removal main basis: With the idea of "high dissolved scale, low dissolved sand", the principle of the synergistic effect of different acids is used to differentiate the dissolution.

2.3.3. Soaking Experiment under Pressure to Evaluate Stabilizer and Acid

Experimental method:

1. Cut loose sandstone gas into standard core (diameter 2.5 cm, length 5 cm), and cover the surface of the core with a layer of a rubber jacket to simulate the formation conditions. The same core is broken apart and named as small core No. 1 and No. 2 to simulate the acid corrosion of a smooth surface and rough surface.
2. After adding hydrochloric acid, a violent reaction occurs, resulting in rock dispersion. Therefore, our group chose several systems to carry out immersion experiments. Core No. 1 was soaked in reservoir stabilizer for 3 h and then put into an acid solution. Core No. 2 was directly put into acid solution, and the corrosion of the acid solution was observed after 24 h.
3. The dissolved rock powder is dried and weighed to compare the reservoir stability effects of different systems.

3. Results and Discussion

3.1. Acid Dissolution Experiment

3.1.1. Conventional Acid

The scale sample was dissolved by acid for 2 h at 45 °C and compared with rocks. The acid solution system used was as follows: 15% hydrochloric acid, 8% hydrofluoric acid, and mud acid (15% hydrochloric acid + 8% hydrofluoric acid). The results show that the scale is almost completely dissolved in hydrochloric acid, which is consistent with the XRD results. However, the dissolution rate of rock powder is 36%, and too much dissolution of the rock will lead to rock dispersion. The rock dissolution rate of hydrofluoric acid is close to that of scale sample, and the rock dissolution rate of soil acid is similar to that of the scale sample. The rock contains quartz and other siliceous material, which is better dissolved in mud acid [22]. At the same time, the above three acids are strong acids, and it is observed that the dissolution reaction degree is very strong during the test, which is very unfavorable to ensure the stability of loose sandstone. The experimental results are shown in Figures 6 and 7.

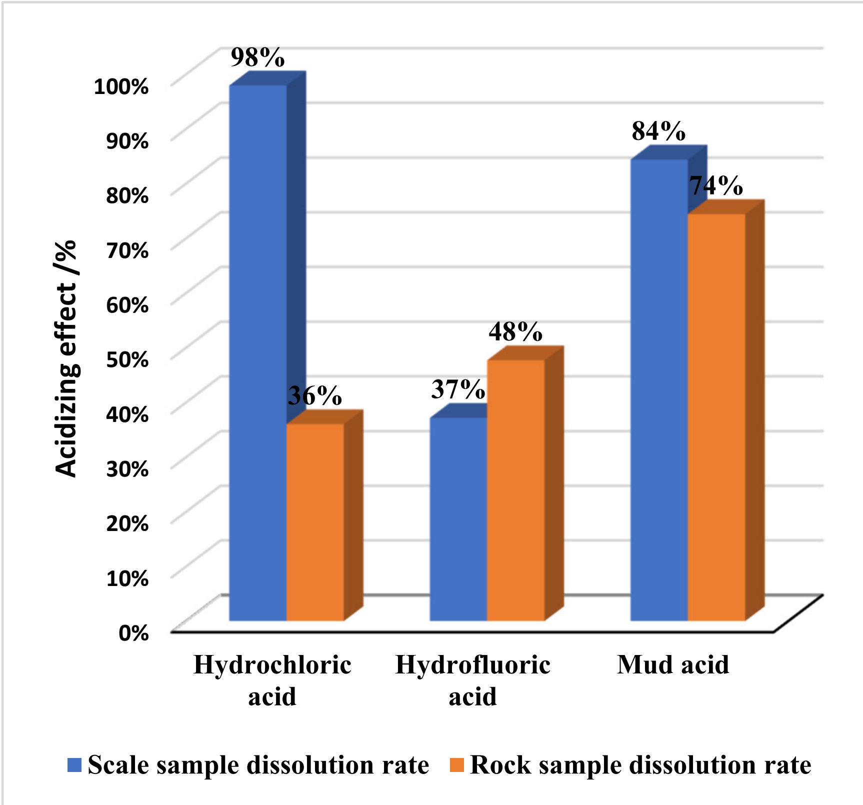


Figure 6. Corrosion results of conventional acid solution.

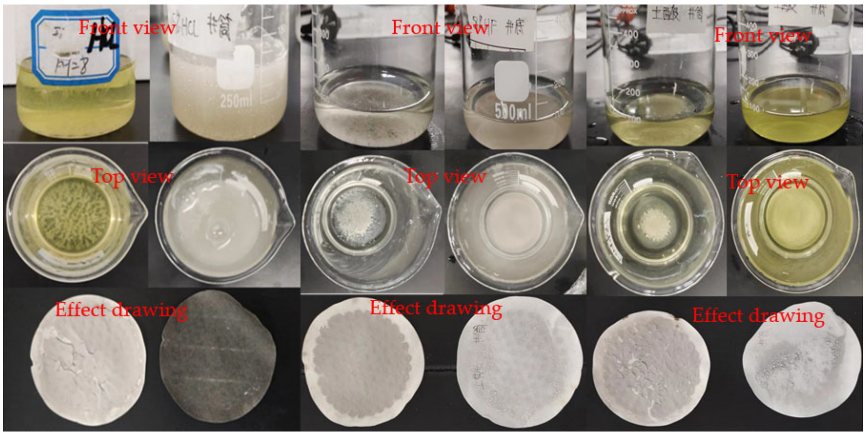


Figure 7. Results of acid dissolution (from left to right: hydrochloric acid, hydrofluoric acid, and mud acid).

3.1.2. Retarded Acid

The experiment of acid dissolution for 2 h was carried out at 45 °C (the formation temperature is 45 °C), and the plugging solution system with large-scale dissolution and a small amount of molten rock was preferred. The slow acid solution system used is the following: 10% solid acid (polycarboxylic acid) [23], 10% HEDP (organic phosphoric acid) [24], and saturated EDTA (amino polycarboxylic acid) [25]. The results show that the solid acid and HEDP can differentially dissolve scale samples and rocks, and the dissolution rates are 97% and ~45%, respectively. The results showed that both solid acid and HEDP were retarded acids, relatively weak in acidity. The chelation of the two can dissolve more scale and less sand [23]. It has a better plugging removal effect and less formation destructiveness. The experimental results are shown in Figures 8 and 9.

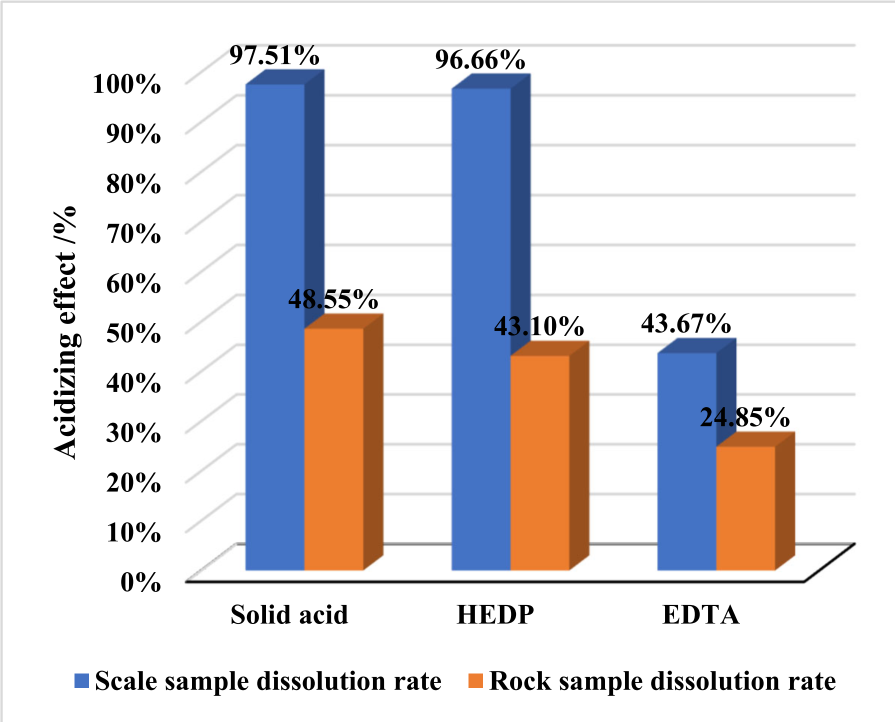


Figure 8. Corrosion results of retarded acid solution.

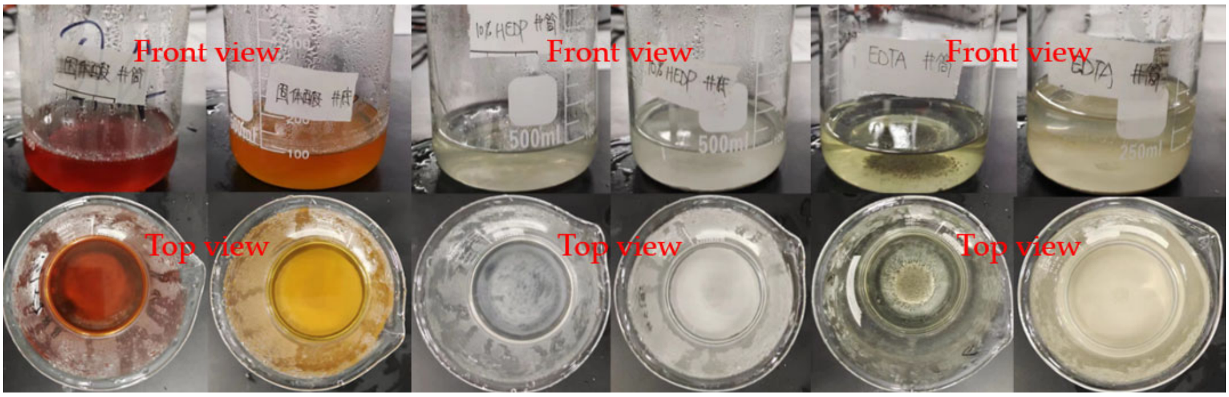


Figure 9. Corrosion results of retarded acid (from left to right: solid acid, HEDP, and EDTA).

3.1.3. Compound Experiment: HCl + Solid Acid + HEDP

According to the contents of Sections 3.1.1 and 3.1.2, we have passed the standard of "high scale, low sand", and three kinds of acid are finally selected: hydrochloric acid, solid acid, and HEDP. Three kinds of acid were mixed and the dissolution effect was observed experimentally. Due to cost reasons, it was decided to use hydrochloric acid as the main ingredient. Finally, hydrochloric acid–solid acid–HEDP = 7:1:2 was selected from six kinds of system as the acid formula. Hydrochloric acid is a strong acid and is the main acid for corrosion. The solid acid is a polycarboxylic acid, which can electrolyze a number of H^+, and the acid can be maintained at a certain acidity during the dissolution process. HEDP is an organic phosphoric acid, which is not only a chelating agent but also has the effect of corrosion and scale inhibition, which can inhibit scale while dissolving scale. Therefore, the combination of the three acids can effectively remove the blockage, the experimental results show that the system can dissolve rock and scale differently, the dissolution rate of the scale sample is more than 95%, the acid corrosion of the rock can be controlled at about 25%, and the integrity of rock can be better guaranteed. The experimental results are shown in Figure 10.

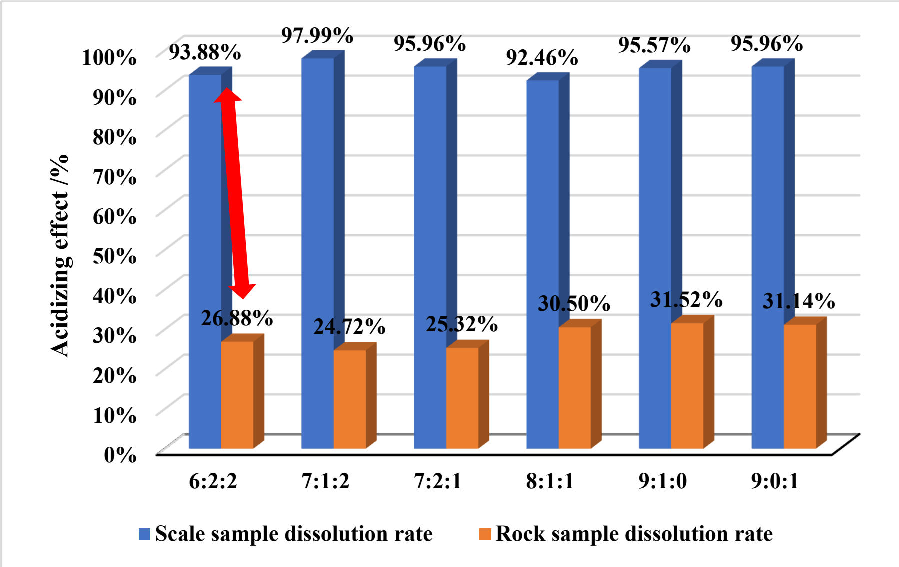


Figure 10. Corrosion results of complex acid solution.

3.2. Immersion Experiment at Normal Temperature and Pressure

Our group added the massive sandstone (1 cm^3) to different concentrations of chemicals, observed its dispersion, and evaluated its reservoir stability effect.

The massive sandstone was added into KCl solutions of different concentrations (1% KCl, 2% KCl, and 4% KCl) to observe its dispersion. As can be seen from Figure 11, the KCl solution has a good effect on clay swelling prevention and can slow down the dispersion rate of rock blocks. However, clay swelling prevention alone is not enough to prevent the dispersion of rock blocks, indicating that clay swelling is not the main reason for its dispersion and migration [26].

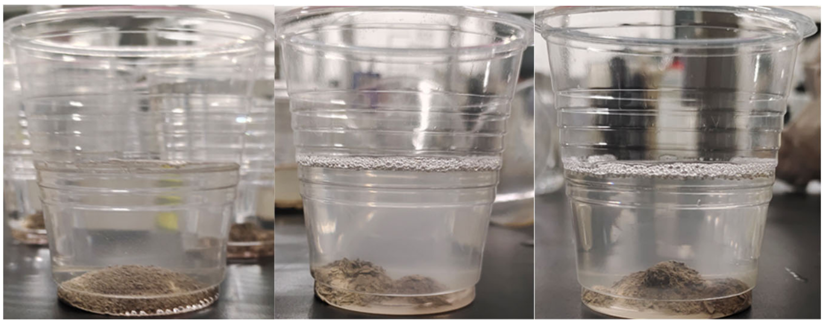


Figure 11. KCl solution immersion experiment (from left to right, 1% KCl, 2% KCl, and 4% KCl).

As a small cationic polymer, polyaluminum chloride has the dual function of the anti-swelling and anti-dispersion of clay, and it has excellent effects in inhibiting the dispersion of the sand body [27]. However, considering that the current unplugging system is an acid solution system, the acid will react to the polymer, causing the molecular chain to break into aluminum trichloride [28], so our group performed immersion experiments with aluminum trichloride and polyaluminum chloride to observe their dispersion.

The results are shown in Figure 12. The results show that polyaluminum chloride has an excellent anti-swelling effect, but aluminum trichloride is not enough to prevent clay expansion. Our group should pay attention to the reaction between the acid and reservoir stabilizer in the subsequent compound acid system.

The nano-emulsion and dodecyl chloropyridine can be added to water to form a new composite colloid system, which can improve the stability and anti-expansion properties of rock blocks. At the same time, rock mass dispersion is slowed down by changing rock wettability. Therefore, our group compared these two surfactants to observe their anti-dispersion effects [29].

Figure 12. Immersion experiment of inorganic cationic polymer (polyaluminum chloride and aluminum trichloride, from left to right).

As shown in Figure 13, both the nano-emulsion and dodecyl pyridine have certain effects on the anti-dispersion of loose sandstone. As can be seen from Figure 13, although the rock was dispersed at the end, the whole structure was sheet-like after dispersion, and it was not completely dispersed. However, the price comparison found that the price of the nano-emulsion was high, so our group chose dodecyl pyridine chloride as the surfactant.

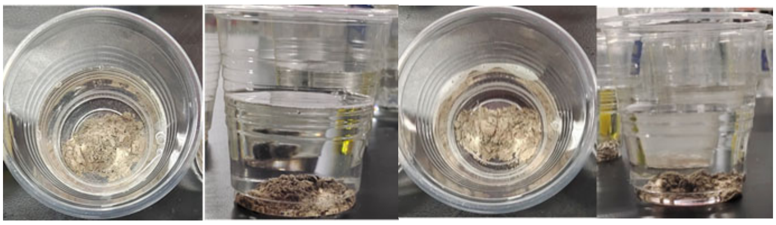


Figure 13. Surfactant immersion experiment (from left to right, nano-emulsion and Dodecyl pyridine chloride).

The addition of hydrochloric acid produced a violent reaction, causing the rock to disperse. The anti-dispersion agent (polyaluminum chloride, pyridine dodecyl chloride, and KCl) was added into the acid solution, and the anti-dispersion effect was observed. The experimental results are shown in Figure 14. The results show that the three systems can inhibit sandstone dispersion to a certain extent, but the inhibition effect will be reduced under acidic conditions. However, the combined anti-dispersion system still has a good inhibition effect.

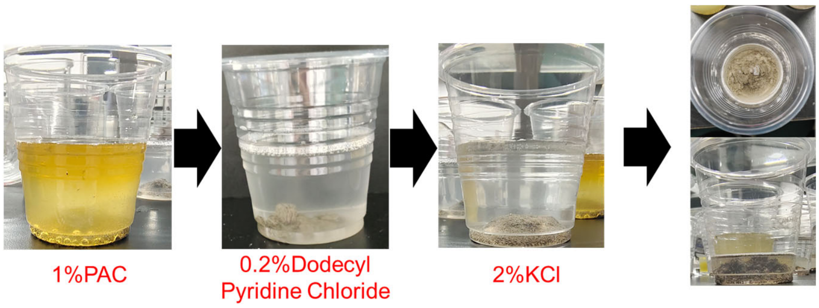


Figure 14. Soaking experiment after compounding.

3.3. Immersion Test in Burden Pressure and Adaptation of Reservoir Stabilizer

In order to simulate the acid corrosion and loose state of unconsolidated sandstone under the conditions of the overlying formation, the unconsolidated sandstone gas was cut into the core, and the surface of the core was covered with a layer of a rubber jacket to simulate the formation's overlying condition. The same core was broken apart and named as small core No. 1 and No. 2 to simulate the acid corrosion of a smooth surface and rough surface. The core diagram is shown in Figure 15.

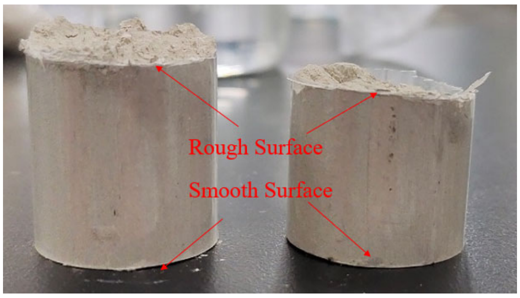


Figure 15. Core picture before acid solution.

The addition of acid creates a violent reaction, causing the rock to disperse. So our group chose two systems: A reservoir stabilizer (polyaluminum chloride, pyridine dodecyl chloride, and KCl) was added to the solution, and its anti-dispersion effect was observed. Then, the reservoir stabilizer was added to the acid solution system and soaked in the acid solution. The other is directly added to the acid system for a comparative test.

Experimental method:

The concentration of the acid solution was 3.5% hydrochloric acid + 0.5% solid acid + 1% HEDP;

Core No. 1 was soaked in reservoir stabilizer for 3 h and then put into the acid solution;

Core No. 2 was directly put into the acid solution, and the acid dissolution was observed after 24 h and 48 h.

(1) No. 1 core:

As can be seen from Figure 16, when the core is soaked in reservoir stabilizer, there is no large-scale collapse phenomenon at both ends of the core, and only a small part of the rock dissolves at both ends. As can be seen from the overall acid corrosion effect diagram, there is no large-scale corrosion of the acid on the core, which proves the anti-dispersion effect of the reservoir stabilizer from the side.

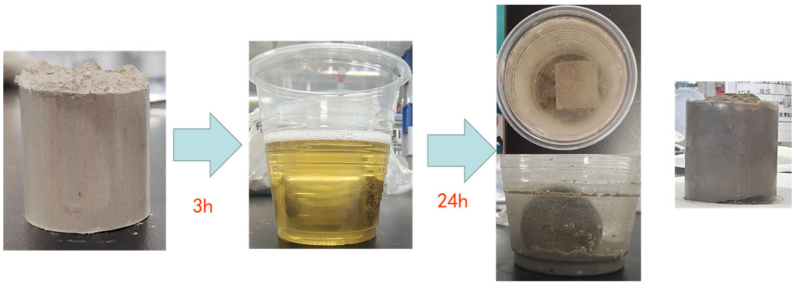


Figure 16. The overall acid corrosion effect diagram of the No. 1 core.

(2) No. 2 core:

As can be seen from Figure 17, core No. 2 was not soaked in reservoir stabilizer, and a large area of collapse occurred at both ends of the core, which was relatively serious, and part of the rock dissolved at both ends. As can be seen from the overall acid corrosion effect diagram, the acid solution corrodes the core in a large area.

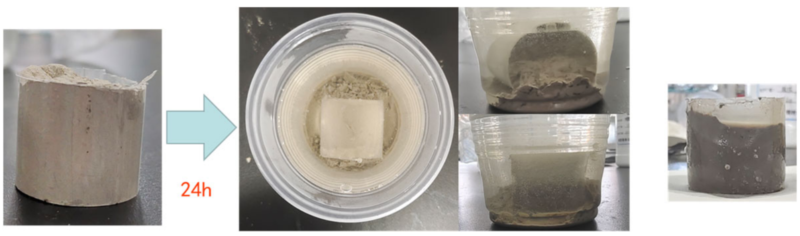


Figure 17. The overall acid corrosion effect diagram of the No. 2 core.

(3) Comparative analysis:

As can be seen from Figure 18:

1. Compared with the No. 2 core, the addition of an inhibitor can effectively reduce the corrosion of acid on the core, and the rock powder is reduced by more than 63% after drying.

2. According to the ratio of the smooth surface to rough surface of the core, it can be seen that the corrosion of the core surface is basically uniform corrosion.

3. According to the height comparison of the rock powder after corrosion of the two cores, it can be seen that the dissolution amount of No. 1 is greatly reduced after the addition of inhibitors, and the volume of dissolved rock blocks is reduced by more than 50%.

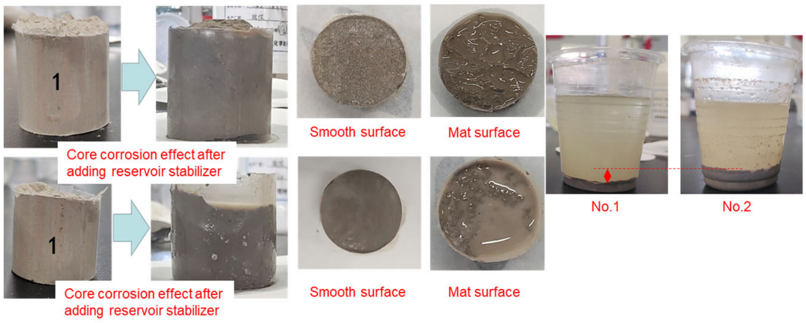


Figure 18. Comparative analysis of the two cores.

The final results show that the three reservoir stabilizers can inhibit sandstone dispersion to a certain extent, but the inhibition effect will be reduced under acidic conditions. The compound dispersion system has a good inhibition effect. The preferred inhibitory dispersant formulation was finally determined as 1% polyaluminum chloride + 0.2% dodecyl benzyl dimethyl ammonium chloride + 2% KCl. Acidification after the addition of inhibitors can effectively reduce the corrosion of acid to the core.

3.4. Field Test

Field tests were carried out on the selected blocking removal system and reservoir stabilization system. The field data are shown in Table 1 and Figure 19. In the field test of eight wells, we selected reservoirs with similar physical properties. We use as a criterion whether the acidification effect is useful. Eight have resumed production, and the gas increase is 0.47 million square meters per day. The average construction fluid volume of the new formula well is 70 cubic meters, and the single cost is 29% lower than that of the conventional formula.

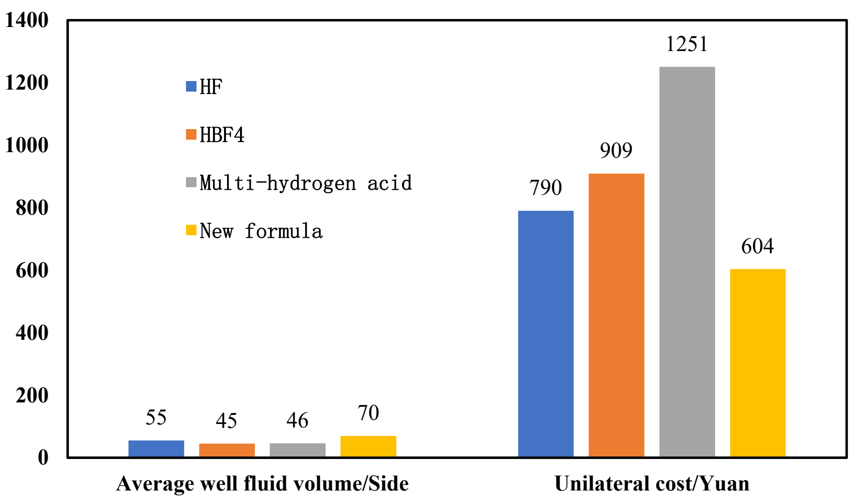


Figure 19. Cost comparison of different formulations.

Table 1. Eight test conditions of 8 wells.

Well Number	Daily Gas (Front)	Daily Gas (Rear)	Daily Gas Increase	Sweep Radius	Acidizing Radius	Preinhibitor	Body Acid	Total Acid Content	Conclusion
1	0.48	0.52	0.08	2	1.45	44	44	88	Efficacious
2	0	0.48	0.48	2.43	1.8	40	40	80	Efficacious
3	0	0.5	0.5	1.95	1.4	44	44	88	Efficacious
4	0	0.3	0.3	2.75	2	16	16	32	Efficacious
5	0	0.53	0.53	2.68	1.98	32	32	64	Efficacious
6	0	0.46	0.46	2.4	1.6	28	28	56	Efficacious
7	0	0.48	0.48	3.75	1.85	40	44	84	Efficacious
8	0	0.56	0.56	2.43	1.8	40	40	80	Efficacious

4. Conclusions

The Sebei gas field is characterized by a high content of shale, poor lithology, intermingling of gas and water layers, and a propensity for sand production. Conventional wisdom suggests that hydrochloric acid is quite effective in alleviating well blockages; however, the loose nature of unconsolidated sandstones tends to exacerbate reservoir dispersion during acid relief operations, intensifying sand discharge. By carefully selecting stabilizers and optimizing acid plugging solutions tailored for unconsolidated sandstone reservoirs, our team has successfully developed a stable sand body plugging fluid system and process methodology. The specific conclusions derived from this research are as follows:

(1) Mineral analysis shows that sandstone is mainly composed of quartz (26.2%) and clay minerals (25%), while clay is mainly composed of illite (68%), which easily leads to reservoir particle migration. The main body of the scale sample is magnesium carbonate (99.8%), and it is almost completely acid-soluble. We started designing acidizing systems based on this.

(2) Hydrochloric acid (strong acid)–solid acid (polycarboxylic acid)–HEDP (organic phosphoric acid) = 7:1:2 is preferred as the plugging removal system, which can differentially dissolve rock and scale, the scale sample dissolution rate is above 95%, the rock acid corrosion can be controlled at about 25%, and the stability of the reservoir can be ensured.

(3) The preferred inhibition dispersant formulation was finally determined as 1% polyaluminum chloride + 0.2% Dodecyl pyridine chloride + 2% KCl. The addition of inhibitors can effectively reduce the acid corrosion of the core by up to 63%.

(4) Field tests show that the new acid solution plugging system can increase the average fluid flow in the well while reducing the cost. The average construction fluid volume of the new formula well is 70 cubic meters, and the single cost is 29% lower than that of the conventional formula.

Suggestion: This experiment is mainly for loose sandstone reservoirs, mainly for dissolving scale samples, to maintain the stability of loose sandstone. When the analog experiment is carried out, the suitable acid system should be selected according to the mineral composition of the sample and the scale sample, and the acid system cannot be directly applied.

Author Contributions: Methodology, D.F. and K.Z.; software, K.Z. and W.S.; validation, H.L. and Q.J.; investigation, K.Z., J.D. and L.L.; data curation, R.K., Y.W. and K.Z.; writing—original draft preparation, K.Z. and B.O.; writing—review and editing, E.Y., D.F. and K.Z.; supervision, K.Z.; funding acquisition, E.Y. and K.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was financially supported by National Natural Science Foundation of China (Grant No. 52004306 and 52174045), the Strategic Cooperation Technology Projects of CNPC and CUPB (Grant No. ZLZX2020-01 and ZLZX2020-02), and the National Science and Technology Major Projects of China (Grant No. 2016ZX05030005 and 2016ZX05051003).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: Wei Song, Daqiang Feng, Qi Jiang, Hai Lin, Li Liao, Ruixin Kang, Baoming Ou, Jing Du and Yan Wang was employed by the Qinghai Oilfield Company. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Li, N.; Jiang, W.; Jiang, Y.; Yang, J.; Cao, G.; Zheng, R.; Feng, D.; Wang, H.; Xu, Z.; Peng, B.; et al. Study into Impacts of Formation Sands on Foam Performance during Drainage Gas Production—Take Qinghai Oilfield's Sebei Gasfield for Example. *Front. Earth Sci.* **2023**, *11*, 1180501. [CrossRef]
2. Zhang, D. Accumulation Conditions and Key Technologies for Exploration and Development in Sebei Gas Field in Qaidam Basin, NW China. *Pet. Res.* **2019**, *4*, 191–211. [CrossRef]
3. Li, L.; Baoming, O.U.; Jun, C.; Cheng, W.U.; Qi, J.; Yong, N.I.; Yu, Z. Plugging Mechanism and Plugging Removal Technology for Unconsolidated Sandstone Gas Reservoirs in Sebei Gas Field. *Xinjiang Pet. Geol.* **2023**, *44*, 100. [CrossRef]
4. Zhou, F.; Yang, X.; Xiong, C.; Zhang, S.; Zong, Y.; Sun, L.; Guan, Z. *Application and Study of Fine-Silty Sand Control Technique for Unconsolidation Quaternary Sand Gas Reservoir, Sebei Qinghai*; OnePetro: Richardson, TX, USA, 2004.
5. Chai, X.; Wang, Y.; Liu, J.; Chen, F.; Yang, H.; Tan, Z. Water-Gas Ratio and Early Warning of Water Invasion in Unconsolidated Sandstone Gas Reservoirs in Sebei Gas Field, Qaidam Basin. *Xinjiang Pet. Geol.* **2023**, *44*, 51.
6. Taha, R.; Hill, A.D.; Sepehrnoori, K. Simulation of Sandstone-Matrix Acidizing in Heterogeneous Reservoirs. *J. Pet. Technol.* **1986**, *38*, 753–767. [CrossRef]
7. Elmgerbi, A.; Thonhauser, G.; Fine, A.; Hincapie, R.E.; Borovina, A. Experimental Approach for Assessing Filter-Cake Removability Derived from Reservoir Drill-in Fluids. *J. Pet. Explor. Prod. Technol.* **2021**, *11*, 4029–4045. [CrossRef]
8. Leong, V.H.; Ben Mahmud, H. A Preliminary Screening and Characterization of Suitable Acids for Sandstone Matrix Acidizing Technique: A Comprehensive Review. *J. Pet. Explor. Prod. Technol.* **2019**, *9*, 753–778. [CrossRef]
9. Shafiq, M.U.; Mahmud, H.B. Sandstone Matrix Acidizing Knowledge and Future Development. *J. Pet. Explor. Prod. Technol.* **2017**, *7*, 1205–1216. [CrossRef]
10. Mahmoud, M.; Gomaa, I. Sandstone Matrix Stimulation. In *Fluid Chemistry, Drilling and Completion*; Wang, Q., Ed.; Oil and Gas Chemistry Management Series; Gulf Professional Publishing: Houston, TX, USA, 2022; pp. 341–386. ISBN 978-0-12-822721-3.
11. Herianto, T. Improving Effective Porosity of Rocks with Matrix Acidizing Stimulation on Sand Stone Formation. *Int. J. Innov. Res. Dev.* **2018**, *7*, 282–292.
12. McCune, C.C.; Ault, J.W.; Dunlap, R.G. Reservoir Properties Affecting Matrix Acid Stimulation of Sandstones. *J. Pet. Technol.* **1975**, *27*, 633–640. [CrossRef]
13. Liu, C.; You, Q.; Wang, T.; Zhou, B.; Peng, W.; Du, Y.; Liu, Y.; Li, Y.; Dai, C. Study of Microscopic Imbibition and Formation Plugging Mechanism of the Compact Oil Reservoir Based on SEM and NMR Analysis. *Fuel* **2024**, *357*, 129672. [CrossRef]
14. Song, W.; Kui, M.; Li, J.; Wang, X.; Liu, J.; Sun, Y.; Wen, Z.; Yang, G.; Tan, X. Key Technologies and Development Countermeasures for Stable Production of Strong Water Intrusion Gas Reservoir in Sebei, Qaidam Basin. *Nat. Gas Ind.* **2023**, *43*, 37–45.
15. Zeng, F.; Zhang, Q.; Guo, J.; Zeng, B.; Zhang, Y.; He, S. Mechanisms of Shale Hydration and Water Block Removal. *Pet. Explor. Dev.* **2021**, *48*, 752–761. [CrossRef]
16. AL-Bazali, T. Insight on the Inhibitive Property of Potassium Ion on the Stability of Shale: A Diffuse Double-Layer Thickness (K−1) Perspective. *J. Pet. Explor. Prod. Technol.* **2021**, *11*, 2709–2723. [CrossRef]
17. Zhang, K.; Yao, E. *Optimization and Evaluation of a Novel Stabilizer Applied to the Strong Water-Sensitive Conglomerate Reservoir*; OnePetro: Richardson, TX, USA, 2023.
18. Wang, T.; Zhang, Y.; Li, L.; Yang, Z.; Liu, Y.; Fang, J.; Dai, C.; You, Q. Experimental Study on Pressure-Decreasing Performance and Mechanism of Nanoparticles in Low Permeability Reservoir. *J. Pet. Sci. Eng.* **2018**, *166*, 693–703. [CrossRef]
19. Wu, W.; Hou, J.; Xiao, L.; Qu, M.; Wang, W.; Stephenraj, I.R.; Wen, Y.; Wu, W.; Liang, T. *Laboratory Study and Field Application of Salt-Tolerant Nano-Emulsion for Enhanced Spontaneous Imbibition Oil Recovery*; OnePetro: Richardson, TX, USA, 2022.
20. Reynolds, M.A. A Technical Playbook for Chemicals and Additives Used in the Hydraulic Fracturing of Shales. *Energy Fuels* **2020**, *34*, 15106–15125. [CrossRef]
21. Kozikhin, R.A.; Daminov, A.M.; Fattakhov, I.G.; Kuleshova, L.S.; Gabbasov, A.K. Identifying the Efficiency Factors on the Basis of Evaluation of Acidizing of Carbonate Reservoirs. *IOP Conf. Ser. Earth Environ. Sci.* **2018**, *194*, 062013. [CrossRef]
22. Shafiq, M.; Shuker, M.; Kyaw, A. Performance Comparison of New Combinations of Acids with Mud Acid in Sandstone Acidizing. *Res. J. Appl. Sci. Eng. Technol.* **2014**, *7*, 323–328. [CrossRef]
23. Alhamad, L.; Alrashed, A.; Al Munif, E.; Miskimins, J. *A Review of Organic Acids Roles in Acidizing Operations for Carbonate and Sandstone Formations*; OnePetro: Richardson, TX, USA, 2020.
24. Chen, Y.; Yang, W. Formulation of Corrosion Inhibitors. In *Water Chemistry*; IntechOpen: London, UK, 2019; 22p.

25. Li, N.; Yang, M.; Zhang, Q.; Zhou, H.; Zhai, C.; Feng, L. *A New Multiple Chelating Acid System with Low Damage and Weak Dissolution*; OnePetro: Richardson, TX, USA, 2019.
26. Wilson, M.J.; Wilson, L.; Patey, I. The Influence of Individual Clay Minerals on Formation Damage of Reservoir Sandstones: A Critical Review with Some New Insights. *Clay Miner.* **2014**, *49*, 147–164. [CrossRef]
27. Hjelmstad, K.E. Cationic Polymers Prevent Permeability Loss during Leaching. *Min. Metall. Explor.* **1990**, *7*, 30–35. [CrossRef]
28. Karmore, V.; Madras, G. Thermal Degradation of Polystyrene by Lewis Acids in Solution. *Ind. Eng. Chem. Res.* **2002**, *41*, 657–660. [CrossRef]
29. Sachin, K.M.; Karpe, S.A.; Singh, M.; Bhattarai, A. An Interaction of Anionic- and Cationic-Rich Mixed Surfactants in Aqueous Medium through Physicochemical Properties at Three Different Temperatures. *J. Chem.* **2018**, *2018*, e4594062. [CrossRef]