Development and Performance Evaluation of Acid Slickwater Fracturing Fluid for Carbonate Reservoir

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Abstract. As the challenges associated with developing carbonate reservoirs intensify, acidized fracturing has emerged as a crucial method for facilitating the efficient extraction of oil and gas. Slickwater fracturing fluid is the most commonly utilized among these options. Nevertheless, its drag reduction capabilities are notably diminished under acidic conditions. In this work, an acid resistance drag reducer PL was selected as the primary material for preparing the acid slickwater, and the concentration of additional additives was optimized. The final formula for the acid slickwater was obtained: 20% HCl + 0.1 wt% PL + 0.05 wt% LQ-B + 0.1 wt% CP-1 + 0.3 wt% CS-1. The rheological and drag reduction properties of the acid slickwater were systematically evaluated. The acid slickwater is a typical pseudoplastic fluid with significant viscoelastic properties. At the displacement of 40 L/min, its drag reduction rate is 75%. In addition, the retention rate of drag reduction exceeded 90% under sustained shear conditions. The acid slickwater developed in this study offers technical support for the effective extraction of resources from deep carbonate reservoirs.

Keywords: Carbonate reservoir; acid slickwater fracturing fluid; high drag reduction rate

1 Introduction

Carbonate oil and gas fields have been discovered and developed globally in 57 sedimentary basins in nearly 40 countries and regions, with oil and gas reserves account for 48% and 28% of the world's total oil and gas reserves, respectively [1, 2]. As conventional oil and gas resources progress into their mid to late stages of development, exploration efforts have increasingly shifted towards deep reservoirs [3, 4]. Deep carbonate reservoir shows the characteristics of nano-pore throat development, which makes oil and gas more difficult to use and has a reduced natural production capacity, so fracturing has become a crucial means to achieve the efficient development of its oil

H. Bilgin et al. (eds.), *Proceedings of the 2024 6th International Conference on Civil Engineering, Environment Resources and Energy Materials (CCESEM 2024)*, Advances in Engineering Research 253,
https://doi.org/10.2991/978-94-6463-606-2_24

and gas [5]. The use of hydrochloric acid can effectively improve the pore structure of carbonate reservoirs and enhance the flow conductivity of supported cracks [6]. Therefore, using acid fracturing process to create fractures and effectively communicate with natural fractures and reservoirs in far-well zones has become one of the key technologies to increase the production of carbonate oil and gas reservoirs [7]. Slickwater fracturing fluid is widely used because of its low cost and easy configuration [3]. However, the drag reduction performance of traditional slickwater fracturing fluid is significantly reduced under acidic conditions, which cannot meet the demands of reservoir development. Thus, it is essential to develop a slickwater fracturing fluid system that exhibits excellent drag reduction performance under acidic conditions, which can combine drag reduction, dissolution, fracture creation, anti-expansion, etc., for the efficient development of carbonate reservoir.

Acid slickwater fracturing fluid mainly consists of drag reducer, corrosion inhibitor, cleanup additive and anti-bulging agent. In this work, the acid slickwater system was constructed by optimizing the type and concentration of fracturing fluid additives with the drag reduction rate as the main evaluation index. Finally, the drag reduction and rheological properties of acid slickwater were evaluated, which is expected to provide technical support for the efficient development of carbonate reservoir.

2 Experimental Part

2.1 Reagents and Instruments

Drag reducer PL was purchased from Shandong Noer Biotechnology Co., Ltd. Hydrochloric acid (HCl), corrosion inhibitors (LQ-A, LQ-B, JA-28), and cleanup additives (CP-1, CP-2, CP-3, CP-4, CP-5) were obtained from Aladdin Reagent Co., Ltd. (China). Anti-bulking agents (CS-1, CS-2, CS-3, CS-4, CS-5) were acquired from Bailingwei Chemical Reagent Co., Ltd.

Instrument: High Temperature High Pressure Interface Rheometer (TRACKER), Rheometer (HAAKE MARS 60), Dynamic Simulation System for Drag Reducing and Carrying Sand (CQJZ-DM), etc.

2.2 Experimental Method

Preparation of Acid Slickwater Fracturing Fluid.

Acid slickwater fracturing fluid consists of drag reducer, corrosion inhibitor, cleanup additive and anti-bulking agent. First, 20% HCl solution was prepared. Then, the polymer drag reducer PL was slowly added to it to avoid the formation of fish eyes. When the drag reducer is completely dissolved, the corrosion inhibitor, cleanup additive and anti-bulking agent were weighed and dissolved into it. After the agitator agitated the solution uniformly, the acid slickwater fracturing fluid was prepared.

Rheology Test.

In the constant shear test, the shear rate was established at 170 s-1. For the steady shear test, the shear rate varied between 10-2-103 s-1. In the viscoelastic test, a stress value of 0.1 Pa was applied, and the scanning frequency range was 0.01-100 Hz.

Drag Reduction Test.

First, 20 liters of water was were introduced into the tank, and the power pump was adjusted so that the liquid can fill the entire test pipeline. Then, the stable pressure difference ΔP1 between two pressure measurement points was recorded. Similarly, after the flow of acid slickwater stabilized in the pipe, the stable pressure difference ΔP2 was noted. After the test, the pipe should be cleaned. The drag reduction rate can be determined using following formula:

$$DR=\frac{\Delta P_1-\Delta P_2}{\Delta P_1} \tag{1}$$

Where DR represents the drag reduction rate of acid slickwater to fresh water, %.

3 Results and Discussion

3.1 Construction of Acid Slickwater System

Optimization of PL Concentration.

The average reduction rates of different concentrations of PL acid solutions (20% HCl) are shown in Fig. 1. The results indicate that the drag reduction rate increases as the concentration of PL rises. However, once the concentration reaches 0.1 wt%, the drag reduction rate stabilizes at about 71.2%. At lower concentrations of the drag reducer, the elastic energy stoblue is inadequate to effectively diminish the energy expenditure associated with turbulent vortices. At higher drag reduction concentrations, the increase of the solution viscosity leads to increased frictional resistance, negatively affecting the drag reduction rate. Consequently, a PL concentration of 0.1 wt% is determined to be the optimal choice for the following experiments.

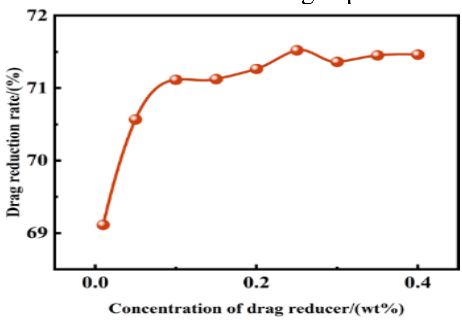

Fig. 1. Drag reduction rate of PL acid solutions at varying concentrations.

Optimization of Corrosion Inhibitor.

In the process of acid fracturing, strong acidic working fluids can cause serious corrosion problems for metal equipment. The addition of metal corrosion inhibitor is a common method to reduce corrosion of equipment by working fluids. Based on the corrosion inhibition rate, the optimal corrosion inhibitor for acid slickwater was screened. The results are depicted in Fig. 2 (a).

When the concentration of the corrosion inhibitor is 0.05 wt%, the corrosion rates of the complex systems of LQ-A, LQ-B and JA-28 corrosion inhibitors and acid slickwater are 43.58 g/(m^2·h), 0.735 g/(m^2·h) and 3.897 g/(m^2·h) respectively. The best corrosion inhibition effect is achieved by LQ-B corrosion inhibitor. Next, the drag reduction properties of acid slickwater containing various corrosion inhibitors were assessed. As the displacement increases, the drag reduction rate of the slickwater also rises. Among them, the acid slickwater with LQ-B corrosion inhibitor shows the best drag reduction effect. The maximum drag reduction rate is 76%. Therefore, considering the corrosion inhibition effect and drag reduction effect, LQ-B is preferred as the corrosion inhibitor of acid slickwater.

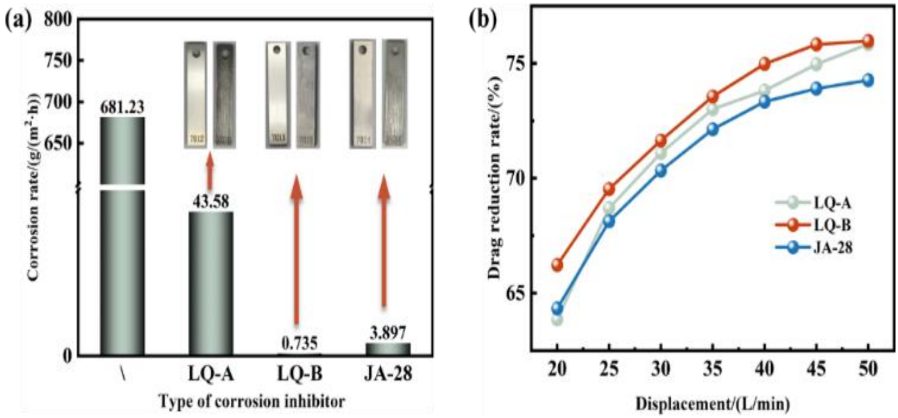

Fig. 2. (a) Corrosion rate of PL and various corrosion inhibitor compound systems. (b) Drag reduction effects of various systems.

Optimization of Cleanup Additive.

The incorporation of cleanup additives into the slickwater effectively lowers the oil-water interfacial tension, thereby reducing the capillary resistance during the return drain. The ability of different types of cleanup additives to reduce surface/interfacial tension was evaluated. The results are presented in Fig. 3 (a) and (b). As the concentration of cleanup additive increases, the surface/interfacial tension of the compound system decreases. Taking surface tension < 32 mN/m and interfacial tension < 3 mN/m as the screening criteria, 0.1 wt% CP-1, 0.4 wt% CP-4 and 0.4 wt% CP-5 all meet the requirements. Subsequently, the compound system of acid slickwater with different cleanup additives was tested for drag reduction performance. With the increase of displacement, the three compound systems all show a gradual increase trend. Among them, the acid slickwater system with CP-1 has the greatest drag reduction rate, which is more than 72%. In comparison, the drag reduction rates of the other two systems are lower than that of the PL acid solution. This is due to the instability of the polymer's structure under strong acidic conditions, which negatively impacts its spatial configuration at high displacement levels, leading to reduced drag reduction effectiveness. Considering the cost, interfacial activity and drag reduction performance, 0.1 wt% CP-1 is finally chosen as the optimal cleanup additive for acid slickwater.

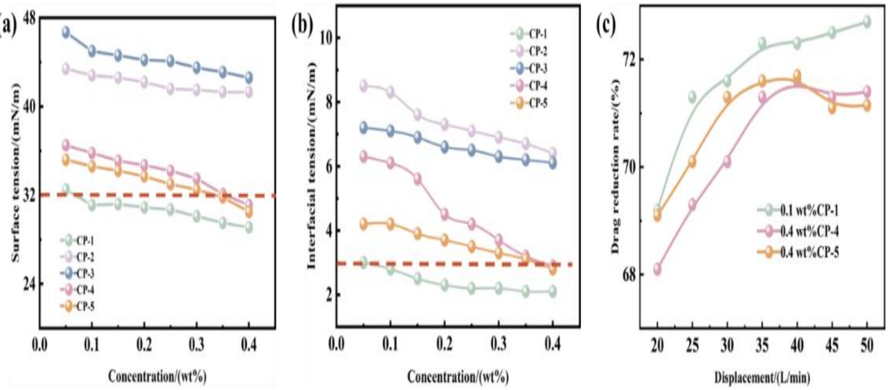

Fig. 3. (a)Surface tension of different compound systems. (b) Interfacial tension of different compound systems. (c) Drag reduction effect of different compound systems.

Optimization of Anti-Bulking Agent.

In the fracturing process, the fracturing fluid will come into contact with clay minerals, and the clay swelling phenomenon often occurs and leads to the reduction of reservoir permeability, which is not conducive to the efficient development of the reservoir. Consequently, the anti-bulking properties of PL in combination with various anti-bulking agents were assessed, as illustrated in Fig. 4 (a).

The results show that with the increase of anti-bulking agent concentration, the anti-bulking rate of acid slickwater is higher. Among them, the compound systems containing 0.3 wt% CS-1, 0.4 wt% CS-2, and 0.4 wt% CS-3 achieved anti-bulking rates exceeding 90%. On this basis, these three anti- bulking agents were chosen to evaluate the drag reduction performance of the compound system. The findings are displayed in Fig. 4 (b). As the displacement increases, the drag reduction effect of the three acid slickwater is increased. Among them, the acid slickwater with CS-1 and CS-2 has the best drag reduction effect, surpassing 75%. In addition, the drag reduction effect of the two systems is not much different, while the concentration of CS-1 used is lower. Therefore, considering the cost, anti-bulking rate and drag reduction rate, 0.3 wt% CS-1 is preferred as the anti-bulking agent of the acid slickwater.

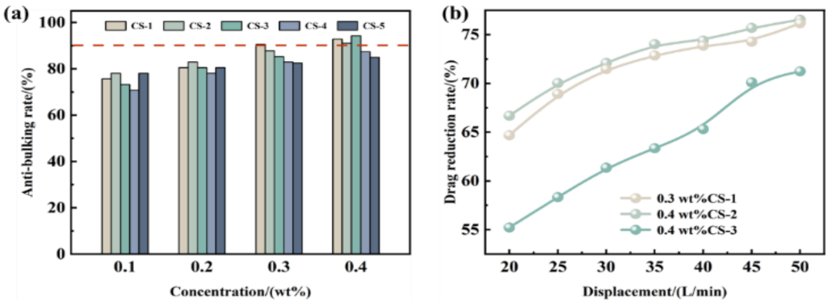

Fig. 4. (a) Anti-bulking rates of PL and various anti-bulking agent compound systems. (b) Drag reduction effects of various systems.

3.2 Performance Evaluation of the Acid Slickwater

Rheological Performance.

In rheology, fluids are usually categorized into Newtonian and non-Newtonian fluids. The Newtonian fluids are significantly affected by temperature, shear stress and shear rate. Fitting the shear stress with the shear rate yields consistency coefficient (K) and flow pattern index (n), as presented in Fig. 5 (a). The value of n can be used to determine the rheological properties of non-Newtonian fluids, while the value of K can indirectly reflect the viscosity of the fluid. The results show that the n = 0.849 and the K = 0.0164 of the acid slickwater fracturing fluid, which indicates that the acid slickwater belongs to a typical pseudoplastic fluid.

The steady shear performance of the acid slickwater is evaluated and the results illustrated in Fig. 5 (b). As the shear rate increased, the viscosity of acid slickwater decreases, showing an obvious shear-thinning phenomenon. At lower shear rates, the viscosity of the acid slickwater remained elevated, primarily due to the slow conformational adjustments of the polymer molecular chain. As the shear rate increases, the polymer molecular chains start to break, leading to the disruption of the network structure and a rapid decline in the viscosity of the acid slickwater. At a higher shear rate, the acid slickwater viscosity tends to stabilize.

By testing the energy storage modulus (G') and loss modulus (G"), insights can be gained regarding the stretching or curling state of the polymer molecular chains. Therefore, the G' and G" of acid slickwater were tested with frequency, and the results are displayed in Fig. 5 (c). G' and G" Both increase with the increasing frequency, and the G' increases more. In the lower frequency range, G" exceeds G', indicating that the fluid's rheological properties are primarily governed by viscosity. Conversely, in the higher frequency range, G' surpasses G", suggesting that elasticity dominates the fluid's rheological behavior. Polymer molecules can store the energy lost in turbulence in their network structures and release the stored elastic potential energy in the low-energy region, thus reducing the energy loss. Therefore, the significant viscoelastic properties of acid slickwater provide the basis for its excellent drag reduction performance.

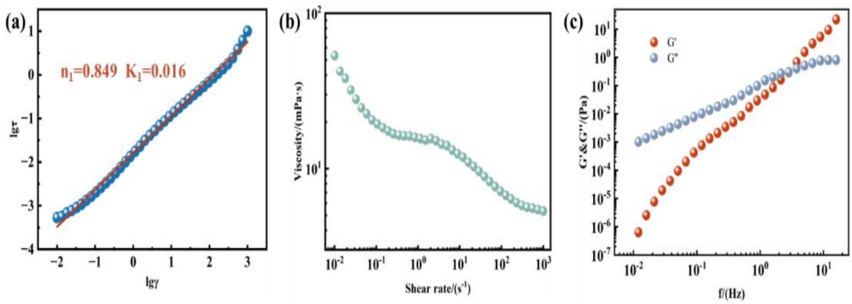

Fig. 5. Rheological properties of acid slickwater. (a) Analysis of flow pattern. (b) Steady shear. (c) Dynamic viscoelasticity.

Drag Reduction Performance.

In order to achieve high displacement injection and maintain the energy of the fracturing fluid into the formation, the drag reduction performance of the slickwater is essential. The drag reduction results are shown in Fig. 6. The evaluation of drag reduction in acid slickwater reveals that, as displacement increases, the drag reduction rate of acid slickwater initially to increase and subsequently tends to be stable. At a displacement of 40 L/min, the drag reduction rate of the acid slickwater reaches the highest, which is 75%, indicating that the acid slickwater has good drag reduction performance. To further investigate the drag reduction of the acid slickwater under continuous high shear conditions, the acid slickwater was subjected to a sustained shear test for 600 s at 40 L/min. The results display that the drag reduction rate of acid slickwater remains stable under prolonged shear, with a retention rate exceeding 90%, indicating that the acid slickwater has excellent shear resistance.

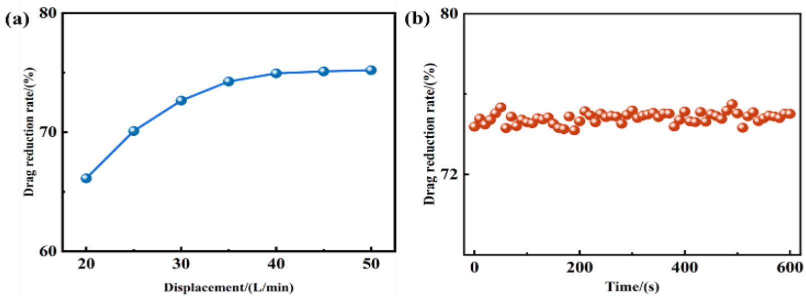

Fig. 6. (a) Drag reduction rate of acid slickwater at various displacement. (b) Drag reduction retention rate of acid slickwater over time.

4 Conclusions

The polymer PL was selected as the drag reducer for acid slickwater fracturing fluid, and its optimal concentration was determined to be 0.1 wt%. Based on acid drag reducer, preferably corrosion inhibitors, cleanup additives and anti-bulking agents. The formula of acid slickwater is: 20% HCl + 0.1 wt% PL + 0.05 wt% LQ-B + 0.1 wt% CP-1 + 0.3 wt% CS-1.

The acid slickwater has good stability at room temperature with an apparent viscosity of 3.52 mPa·s. The rheological properties of acid slickwater were evaluated, including steady shear and dynamic viscoelasticity. The acid slickwater achieves a drag reduction of 75% at the displacement of 40 L/min, and the drag reduction retention rate is more than 90% under prolonged high-speed shear.

Acknowledgment

We gratefully acknowledge the financial support from the National Natural Science Foundation of China (52288101, 52120105007), the National Science Fund for Distinguished Young Scholars (52222403), the Taishan Scholar Expert (tsqn202211079, tspd20230605).

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