Article

Study on the Alkali-Free Three-Component Flooding System in the Daqing Oilfield

Xiaoying Liu,* Hao Wu, Sian Chen, Jingang He, Zhao Yang, Jiecheng Cheng, and Jingchun Wu

Cite This: *ACS Omega* 2024, 9, 16006−16015

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ABSTRACT: ASP flooding is an important method to further improve oil recovery by a large margin. At present, it has entered the stage of industrial application, but there are still problems of scaling in the injection production system and high production maintenance costs. Based on the industrialized mature technology of weak alkali ASP flooding, sodium chloride is used to replace sodium carbonate, and the alkali-free three-component flooding (TC) system in the Daqing Oilfield is developed by mixing with petroleum sulfonate and partially hydrolyzed polyacrylamide. Based on the experiments of viscosity increasing, interface performance, stability, adsorption, and oil displacement effect, the differences between the alkali-free TC system and the weak alkali ASP system are compared and analyzed. The laboratory research results show that both systems are basically the same in terms of viscosity, viscoelasticity, shear resistance, interfacial activity, stability, and flowability. Due to the lack of alkaline water, the adsorption, emulsification, and oil displacement performance of the alkali-free TC system is slightly lower than that of the weak alkali ASP system. The recovery factor of core flooding can be increased by 27.31% over water flooding, which is 2.56 percentage points lower than that of the weak alkali ASP system. On the premise of the same 1% EOR effect, the agent cost of the alkali-free system is 17.02% lower than that of the alkali ASP system. This article innovatively verifies the feasibility of using NaCl instead of Na_2CO_3 and explains the mechanism of significantly improving oil recovery in composite systems under alkali-free conditions from the ion level. However, the emulsification effect of the alkali-free TC system is relatively weak. The next step of research would be to consider adding an E-surfactant to enhance the emulsification performance of the composite system. By improving the system composition, technical references are provided for the efficient development of other terrestrial sandstone oilfields.
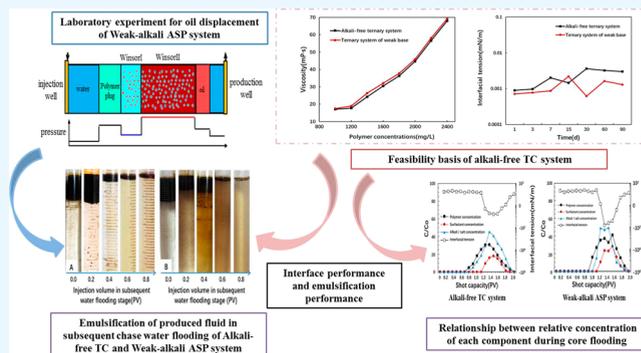
1. INTRODUCTION

At present, energy exploitation is diversified,[1,2] and ASP flooding technology is often used to extract crude oil in the Daqing area. The ASP flooding technology is a technology that greatly improves oil recovery on the basis of alkali/polymer flooding and surfactant/polymer flooding. The ASP system is composed of an alkali, a surfactant, and a polymer. It increases the viscosity of the injection system and expands the swept volume. At the same time, it reduces the oil−water interfacial tension and improves the oil washing efficiency and ultimately achieves a significant increase in oil recovery.[3−6] The United States has successively carried out pilot tests of small-scale ASP flooding technology in West Kiehl oilfield (1987),[7] Cambridge oilfield (1993),[8] Tanner oilfield (2000),[9] Lawrence (2010),[10] etc. Due to poor technical and economic benefits, it has not been industrialized and promoted.[11] China 's Daqing Oilfield began to study the ASP flooding technology since the 1980s,[12] breaking through the theoretical constraints that low acid value crude oil is not suitable for ASP flooding and realizing the independent production of surfactants.[13] Following four stages

of laboratory investigation, pilot field testing, industrial field testing, and industrialization promotion, the technology has reached a relatively advanced stage of development. Based on water flooding, it has been observed that the implementation of ASP flooding in the Daqing Oilfield can result in a significant improvement of over 20.0 percentage points in oil recovery, thus establishing itself as a crucial method for enhancing oil recovery. The widespread adoption of ASP flooding on an industrial scale was initiated in the Daqing Oilfield in 2014. In the aforementioned year, the production escalated to 2 million tons, marking the first instance of such magnitude. Subsequently, in 2016, the production of crude oil
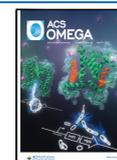
Table 1. Ion Content of Experimental Water

water sample	ion content (mg/L)							mineralization (mg/L)
	Cl^-	HCO_3^-	CO_3^{2-}	SO_4^{2-}	Ca^{2+}	Mg^{2+}	$Na^+ + K^+$	
fresh water	44.5	230.0	15.1	5.0	37.8	2.6	81.3	416.3
back to the water injection	943.8	2821.2	301.6	5.0	42.0	5.1	1851.5	5970.6
simulation formation water	2155.8	2063.5		287.5	23.1	52.6	2196.5	6779.0

surpassed 4 million tons, with the annual oil production in the preceding six years consistently exceeding this threshold. This achievement significantly contributed to the sustained high yield of the Daqing Oilfield and positioned China as the sole nation globally to possess expertise in the industrial technology of ASP flooding.[14,15]

The commonly used types of surfactants in oilfields include anionic, nonionic, and anionic nonionic types. Surfactants mainly improve crude oil recovery by reducing oil–water interfacial tension, changing rock wettability, enhancing emulsifying ability, and other mechanisms.[16] At present, the surface-active agent widely used in weak alkaline ASP flooding blocks in the Daqing Oilfield is sulfonate, which could significantly enhance oil recovery performance under alkaline conditions. However, the alkali in the ternary composite flooding can easily cause scaling in the injection production system, which brings certain difficulties to production management and also increases maintenance workload and operating costs.[17] Consequently, in 2005, the Daqing Oilfield adopted a development strategy for ASP flooding, transitioning from strong alkali to weak alkali and ultimately eliminating alkali altogether. In the investigation and advancement of alkali-free binary composite systems, there exists a current deficiency of efficient and stable surfactant industrial products that are suitable for implementation in the Daqing Oilfield. The accompanying technology necessary for conducting pilot tests lacks maturity, thereby necessitating further technical research.[18,19] Additionally, in terms of enhanced oil recovery performance, the indoor core flooding experiment conducted on alkali-free binary composite systems yields results that are 3–5 percentage points lower than those obtained from ternary composite systems.[20−22] Hence, the pursuit of an alternative chemical agent to replace alkali in the formation of a novel ternary composite system, ensuring the efficacy of oil displacement, has emerged as a pivotal focus for the Daqing Oilfield, bearing immense significance.

Utilizing the established industrial technology of weak alkali ASP flooding, the research team employed sodium chloride as a substitute for sodium carbonate to devise an alkali-free TC system in the Daqing Oilfield. By conducting an assessment of viscosity, interfacial activity, stability, antiadsorption, and oil displacement performance, a comprehensive comparison and analysis of the disparities in performance between the alkali-free TC system and the weak alkali ASP system were undertaken by the authors. In comparison to the weak alkali ASP system, the alkali-free TC system demonstrates a comparable oil displacement performance while achieving a further reduction in the cost of chemical agents. This realization of alkali-free ASP flooding offers significant technical support for the advancement of ASP flooding.

2. MATERIALS AND METHODS

2.1. Experimental Materials. The chemical reagents used in this study included sodium chloride (NaCl) and sodium carbonate (Na_2CO_3), both of which are industrial products with a solid content exceeding 99.2%. Additionally, petroleum sulfonate, an industrial product with an effective content ranging from 38 to 42%, and partially hydrolyzed polyacrylamide (HPAM), an industrial product with a molecular weight of 16 million and a solid content exceeding 88.0%, were also utilized. The experimental water used in this research consists of clear water, oilfield deep treatment reinjection water, and simulated formation water, with their respective ion compositions provided in Table 1. The experimental study utilized dehydrated and degassed crude oil extracted from block A of the Daqing Oilfield ASP flood industrialization promotion. The crude oil had a density of 847.5 kg/m³ and a dynamic viscosity of 27.22 mPa·s at a temperature of 45 °C. To simulate the oil, a mixture of dehydrated degassed crude oil and aviation kerosene was prepared, resulting in a dynamic viscosity of 10.0 mPa·s at 45 °C. The oil sands used in the study were obtained from the Daqing Oilfield ASP flooding industrialization promotion A block SII reservoir group. The core samples consisted of Bailey sandstone with dimensions of 45 mm × 45 mm × 300 mm.

2.2. Experimental Apparatus. TX-500 C ultralow interfacial tension meter, Kono Industrial Co., Ltd.; Brookfield DV-II viscometer, Brookfield; multifunctional oil displacement device, Haian Petroleum Technology Co., Ltd.; t25 digital display disperser, IKA, Germany.

2.3. System Preparation. The ternary composite system employs the sewage dilution method. A 5000 mg/L partially hydrolyzed polyacrylamide mother liquor is prepared by injecting water, stirring for 2.0 h, and ripening for 2.0 h. Additionally, 5.0% petroleum sulfonate mother liquor, 5.0% sodium carbonate mother liquor, and 5.0% sodium chloride mother liquor are prepared by injecting water. Partially hydrolyzed polyacrylamide, petroleum sulfonate, sodium carbonate, or sodium chloride mother liquor are added according to the system ratio, and the resulting solution is obtained by adding back water and stirring until evenly mixed. The alkali-free TC system comprises petroleum sulfonate, sodium chloride, and partially hydrolyzed polyacrylamide, while the weak base ternary system comprises petroleum sulfonate, sodium carbonate, and partially hydrolyzed polyacrylamide.

2.4. Determination of Shear Resistance. The initial viscosity of a weak alkali ASP system solution was measured and subsequently presheared to reduce its viscosity to 60% of the prepared viscosity. The duration of shear was recorded, followed by preshearing the alkali-free TC system at the same shear rate and duration. The impact of shear was assessed based on the difference in viscosity.

2.5. Experimental Materials. The alkali-free TC system and weak alkali ASP system were prepared using 2000 mg/L partially hydrolyzed polyacrylamide, 0.05−0.3 wt % petroleum sulfonate, 0.2−1.4 wt % sodium chloride, and 0.2−1.4 wt % sodium carbonate. The interfacial tension between the different system solutions and dehydrated and degassed crude oil in block A was measured at 45.0 °C using the

TX500C rotating ultralow interfacial tension meter.[23,24] The stability of the systems was evaluated by continuously measuring the changes in the interfacial tension over a period of 90 days.

2.6. Determination of Emulsification Water Separation Rate. Various system solutions were combined with the simulated oil in a volumetric ratio of 1:1. The resulting mixture was homogenized at a speed of 10,000 rpm for a duration of 2 min, resulting in the formation of an emulsion. Subsequently, the emulsion was subjected to a constant temperature of 45.0 °C in order to assess the rate at which water separated from the emulsion at different time intervals.

2.7. Determination of Antiadsorption Capacity. The antiadsorption capacity was assessed using a multiple adsorption experiment on oil sand.[25] A quantity of 20 g of oil sands, ranging from 80 to 120 mesh, was measured and placed into a 250 mL triangular flask. Subsequently, the ternary composite system solution was added to the flask at a solid−liquid mass ratio of 1:9. The flask was then sealed and placed in a constant temperature shaker, where it was oscillated at 45.0 °C for a duration of 24.0 h. A small portion of the upper liquid was extracted to determine the interfacial tension between the system and crude oil, which was recorded as the interfacial tension value of the system following one adsorption. Throughout multiple adsorptions, the entirety of the liquid in the upper layer was extracted and the oil sand was subsequently reintroduced in accordance with the aforementioned solid−liquid mass ratio. The aforementioned procedures were iterated to acquire the interfacial tension measurement of the system following multiple adsorptions, thereby facilitating a comparative and analytical assessment of the surfactant's antiadsorption capability across the three systems.

2.8. Cores Experiment. Bailey core vacuum was used, the saturated simulated oil was aged for 72.0 h, and the initial oil saturation was calculated. Water flooded to the outlet water content of more than 98.0%, followed by the injection of three kinds of system main slug and polymer protection slug (core displacement experiment scheme is shown in Table 2),

Table 2. Experimental Scheme for Core Flooding Tests

flooding system	concrete schemes
alkali-free TC system	main slug: 0.3 PV (2000 mg/L 16 million HPAM + 0.3 wt % petroleum sulfonate + 1.2 wt % NaCl)
	protective slug: 0.2 PV (1600 mg/L 16 million HPAM)
ternary system of weak base	main slug: 0.3 PV (2000 mg/L 16 million HPAM + 0.3 wt % petroleum sulfonate + 1.2 wt % Na$_2$CO$_3$)
	protective slug: 0.2 PV (1600 mg/L 16 million HPAM)

followed by water flooding to the water content of more than 98.0%. At a temperature of 45 °C, the saturated oil velocity is measured to be 0.1 mL/min, while the displacement velocity is recorded as 0.3 mL/min, which is approximately equivalent to the displacement velocity observed at the leading edge of the reservoir, estimated to be 1 m/days.

2.9. Determination of Produced Fluids in Core Displacement Experiment. The concentrations of the polymer, surfactant, sodium chloride (in the alkali-free TC system), sodium carbonate (in the weak alkali ASP system), and interfacial tension in the produced fluid were measured for each stage of the core flooding experiment. The criteria for determination were based on the "SY/T6424-2014 composite

flooding system performance test method", "SY/T5862-2020 polymer technical requirements for oil displacement", and "SY/T5523−2016 oilfield water analysis method".

3. RESULTS AND DISCUSSION

3.1. Feasibility Basis of the Alkali-Free TC System. There are three main aspects of alkali flooding in ASP. First, alkali reacts with petroleum acids in crude oil to form surface-active compounds. Sodium carbonate is an alkaline aqueous solution in the weak base ternary system, and surface-active substances are generated when the alkali reacts with petroleum acid, reducing the interfacial tension between oil and water.

Daqing crude oil, however, has a low acid value, and isomeric acid makes up only 0.0059% of the crude oil. Hence, the quantity of surface-active substances is limited and solely the initial adsorption on the surface of oil droplets contributes to the reduction of dynamic interfacial tension, while subsequent diffusion into the bulk phase diminishes the efficacy of interfacial tension reduction. Furthermore, when subjected to alkaline conditions, the nitrogen-containing heterocyclic compounds present in the resins and asphaltenes of Daqing crude oil, accounting for 0.16% of its mass, engage in interfacial diffusion with the active substances generated through alkali-induced reactions.

This interaction, in conjunction with petroleum sulfonates, synergistically diminishes the interfacial tension between the oil and water. Notably, this reduction in tension is comparable to the impact of organic acids found in crude oil. The impact of the pH value on the dynamic interfacial tension between the ternary system and crude oil was investigated through the utilization of sodium chloride and sodium hydroxide in varying proportions. The obtained results, as depicted in Figure 1,
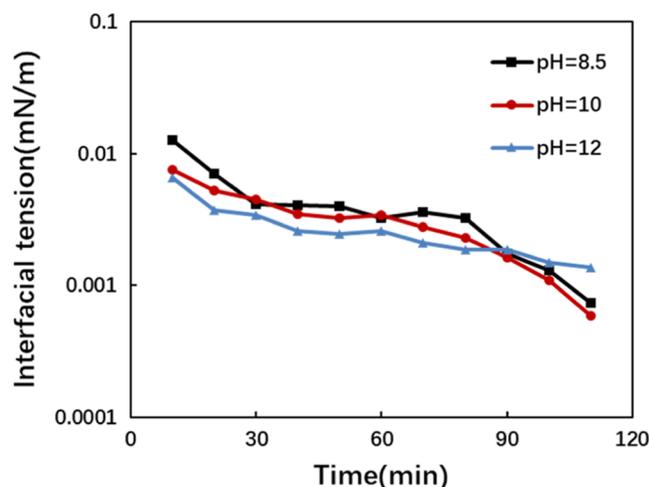
Figure 1. Effects of pH on oil−water interfacial tension for the ASP flooding system. (ASP flooding system: 2000 mg/L 16 million HPAM + 0.3 wt % petroleum sulfonate + 1.2 wt % Na$_2$CO$_3$).

indicate a marginal reduction in interfacial tension with increasing pH value, albeit at a sluggish rate. Once the test duration reaches 110 min, the ultralow interfacial tension range can ultimately be attained. Consequently, the alteration of pH from 8.5 to 12 exhibits a relatively negligible impact on the interfacial tension existing between the ASP flooding system and Daqing crude oil.

Additionally, weak alkaline conditions facilitate the presence of the Na$^+$ concentration. The release of Na$^+$ resulting from the

(a) Alkali-free TC   (b) Weak-alkali ASP
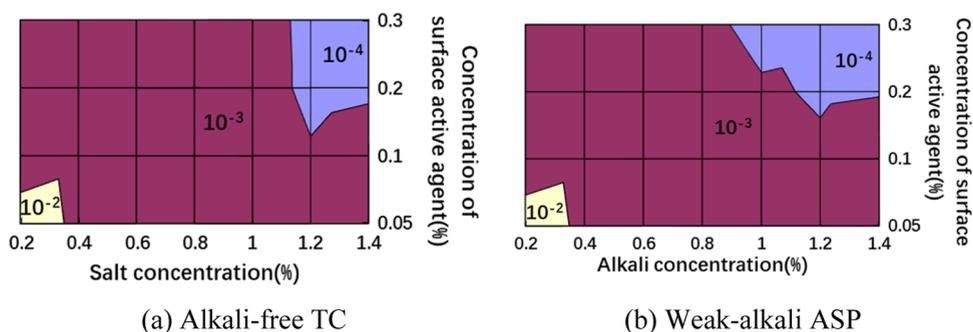
**Figure 2.** Interfacial activities between the system and different crude oil.

dissociation of sodium carbonate leads to its diffusion into the oil−water interface layer. This diffusion process serves to neutralize the repulsive force between the surfactant molecules, thereby compressing the thickness of the electric double layer. Consequently, the surfactant molecules become more evenly distributed at the oil/water interface.

Additionally, Na^+ causes the polyacrylamide molecules in the composite system to curl up, which reduces the positional competition between polyacrylamide and petroleum sulfonate molecules at the interface. This indirect effect ultimately accelerates the speed of the composite system, facilitating the achievement of ultralow interfacial tension.[26,27] Hence, by integrating the examination of alkali action and the advancement of petroleum sulfonate surfactant performance, it becomes feasible to substitute sodium chloride for sodium carbonate in order to achieve alkali-free ASP flooding.

3.2. Evaluation of Interface Performance of the Alkali-Free TC System. *3.2.1. Interfacial Activity.* The measurement of the interface performance serves as a crucial metric for assessing the oil displacement capacity of the system. Figure 2 illustrates the interface properties of the two ternary composite systems. The findings indicate that by maintaining a concentration range of petroleum sulfonate between 0.05 and 0.3 wt % and a concentration range of sodium chloride and sodium carbonate between 0.4 and 1.4 wt %, both systems and crude oil can attain an ultralow interfacial tension in the order of magnitude of 10^{-3} mN/m. When the concentration range of petroleum sulfonate is between 0.2 and 0.3 wt %, and the concentration range of sodium chloride and sodium carbonate is between 1.2 and 1.4 wt %, the resulting interfacial tension can reach magnitudes of 10^{-4} mN/m.

Specifically, the alkali-free TC system exhibits an interfacial tension of 4.8×10^{-4} mN/m, while the weak alkali ASP system exhibits an interfacial tension of 2.9×10^{-4} mN/m. Given that the relative molecular weights of sodium chloride and sodium carbonate are 58.5 and 106.0, respectively, it is possible to provide Na^+ with comparable concentrations when the mass fractions of sodium chloride and sodium carbonate in the solution remain consistent. Consequently, a greater quantity of petroleum sulfonates can be evenly dispersed within the oil− water interface layer. Therefore, the interface performances of the two systems are basically the same.

3.2.2. Stability of Interfacial Tension. The alterations in interfacial tension for both systems were assessed over a period of 90 days, as depicted in Figure 3. In the alkali-free TC system, the interfacial tension escalated from an initial value of $(8.91 \times 10^{-4})−(3.02 \times 10^{-3})$ mN/m after 90 days. Similarly, the interfacial tension of the weak base ternary system rose from 7.1×10^{-4} to 1.3×10^{-3} mN/m. The experimental
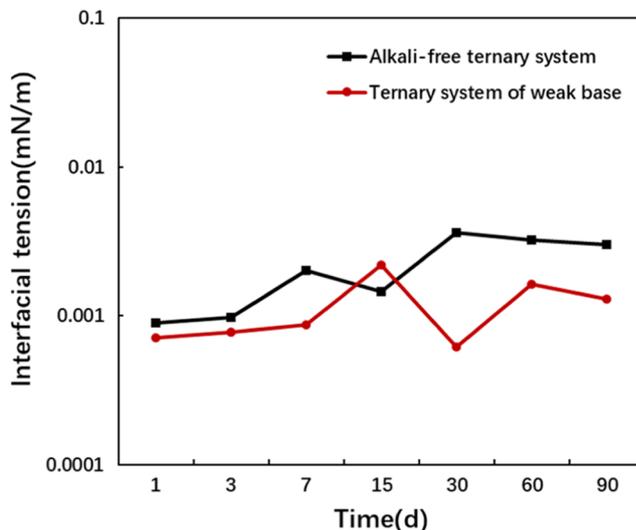
Figure 3. Interfacial tension stabilities of the alkali-free TC and weak alkali ASP system.

findings indicate that the interfacial tension stability of both systems remains relatively consistent over a period of 90 days. Moreover, it demonstrates commendable stability, as it consistently maintains a value below 10^{-3} mN/m.

3.2.3. Oil Sand Adsorption Resistance. During the migration of surfactants in the pores of reservoir rocks, there is a propensity for them to adsorb and accumulate on the surface of the rocks. This phenomenon subsequently results in a decrease in the concentration of surfactants within the displacement system. Moreover, the increased adsorption capacity has a detrimental effect on the effectiveness of oil displacement. To investigate this, antiadsorption measurement experiments were conducted on oil sands with a particle size ranging from 80 to 120 mesh. The alterations in interfacial tension values before and after adsorption of the two systems were compared and analyzed. The findings are presented in Table 3, indicating that the interfacial tension values of both systems persist at approximately 10^{-3} mN/m following three adsorptions. However, after the fourth adsorption, the interfacial tension value of the alkali-free TC system escalated to approximately 10^{-2} mN/m, whereas the interfacial tension value of the weak alkali ASP system remained at approximately 10^{-3} mN/m. This discrepancy can be attributed to the heightened electronegativity of the rock surface in an alkaline environment and the diminished adsorption capacity of the anionic surfactants. The findings are presented in Table 3, indicating that the interfacial tension values of both systems

Table 3. Antiadsorption Performance Data of the Weak Alkali ASP and Alkali-Free TC Systems

	interfacial tension ($\times 10^{-3}$ mN/m)					
system	nonadsorbed	first adsorption	second adsorption	third adsorption	fourth adsorption	fifth adsorption
alkali-free TC system	0.9	4.78	5.51	8.77	30.5	
week alkali ASP system	0.7	2.38	3.57	7.75	5.51	15.5

persist at approximately 10^{-3} mN/m following three adsorptions. However, after the fourth adsorption, the interfacial tension value of the alkali-free TC system escalated to approximately 10^{-2} mN/m, whereas the interfacial tension value of the weak alkali ASP system remained at approximately 10^{-3} mN/m. This discrepancy can be attributed to the heightened electronegativity of the rock surface in an alkaline environment and the diminished adsorption capacity of anionic surfactants.

3.3. Evaluation of Thickening Performance of the Alkali-Free TC System. The thickening effect of polymers plays a significant role in chemical flooding methods aimed at improving oil recovery.[28,29] Figure 4 illustrates the viscosity of
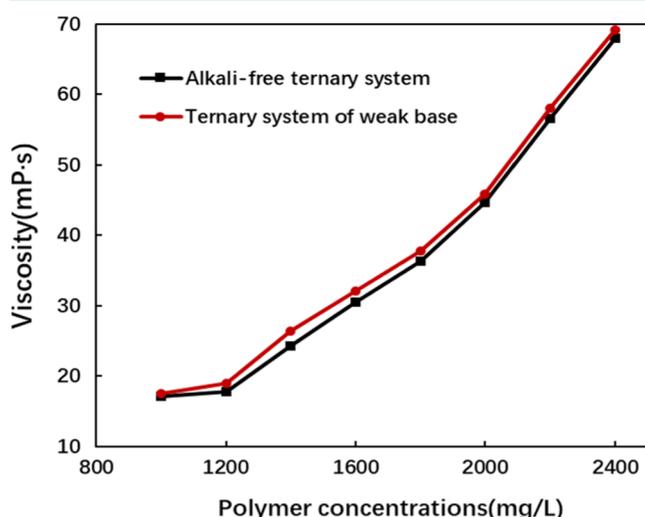

Figure 4. Viscosity−concentration curves of alkali-free TC and weak alkali ASP system;.

the two systems at various polymer concentrations. The findings indicate that the viscosity−concentration relationship of the alkali-free TC system closely resembles that of the weak alkali ASP system within the polymer concentration range of 1000−2400 mg/L. At a polymer concentration of 1600 mg/L, the alkali-free TC system exhibits a viscosity of 30.5 mPa·s, while the weak alkali ASP system exhibits a viscosity of 31.9 mPa·s, resulting in a difference of 4.4%. The viscosity of the ternary system solution is primarily influenced by the type and concentration of cations present. In both the alkali-free and the weak alkali ASP systems, the predominant cation is Na^+. When the mass fraction of sodium chloride and sodium carbonate in the solution is equivalent, the molar quantity of Na^+ closely approximates the ion content.[30] Hence, the replacement of sodium carbonate with sodium chloride does not exert any influence on the viscosity of the system. Moreover, the viscosity of the alkali-free TC system aligns closely with that of the weakly alkali ASP system.

The enhancement of microscopic oil displacement efficiency is significantly influenced by the "pulling and pulling" effect generated by the viscoelastic polymer solution. The viscoelastic

properties of the system were assessed by measuring the first normal stress difference of the two system solutions, as depicted in Figure 5. Both systems exhibit comparable first
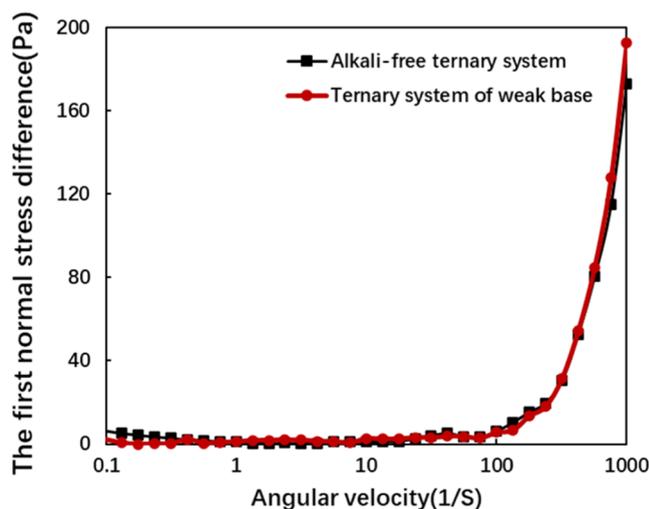

Figure 5. Viscoelastic curve of the alkali-free TC and weak alkali ASP system.

normal stress differences when subjected to identical angular velocity conditions. Consequently, the viscoelasticity of the alkali-free ternary complex is essentially equivalent to that of the weakly alkali ASP system.

The stability of the viscosity is a crucial parameter for characterizing the long-term stability of an oil displacement system. Figure 6 presents the evaluation results of the viscosity stability for both systems. In the alkali-free TC system, the viscosity decreased from 30.5 to 25.2 mPa·s after 90 days,
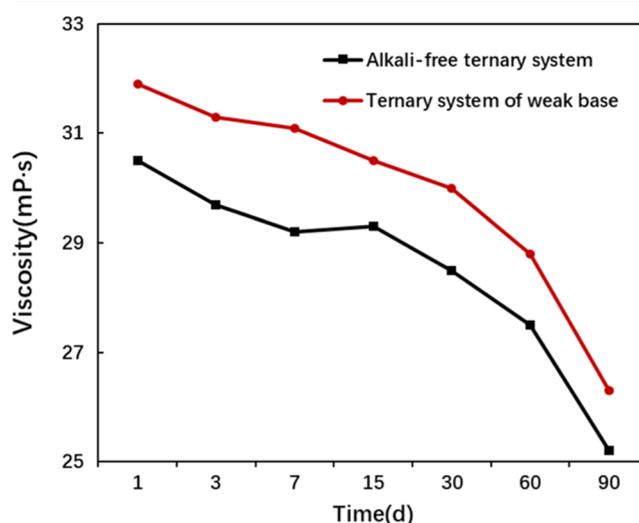

Figure 6. Viscosity stabilities of alkali-free TC and the weak alkali ASP system.

resulting in a viscosity retention rate of 82.62%. Similarly, the weak alkali ternary composite system exhibited a decrease in viscosity from 31.9 to 26.3 mPa·s at 90 days, with a viscosity retention rate of 82.46%. The viscosity stability of both the alkali-free TC system and the weak alkali ASP system exhibited a similar trend over a period of 90 days, with values consistently above 80%.

The IKAT25 digital display dispersion machine was utilized to subject the alkali-free TC system and the weak alkali ASP system to shear. The outcomes of the experiments are presented in Table 4. The findings indicate that, when

Table 4. Test Data of Shear Stability Analysis

system	initial viscosity (mPa·s)	postshear viscosity (mPa·s)	viscosity retention (%)
alkali-free TC system	35.3	21.7	61.47
weak alkali ASP system	36.2	22.5	62.15

subjected to the same shear rate and shear time, the alkali-free TC system and the weak alkali ASP system exhibit similar viscosity retention rates after shearing. Specifically, the alkali-free TC system displayed an initial viscosity of 36.2 mPa·s and a postshear viscosity of 22.5 mPa·s, resulting in a viscosity retention rate of 62.15%. The weak base ternary system exhibited an initial viscosity of 35.3 mPa·s and a postshear viscosity of 21.7 mPa·s, resulting in a viscosity retention rate of 62.47%. The reduction in viscosity following shearing can be attributed primarily to the fracture of the polymer molecule's long chain. Notably, the presence of sodium chloride and sodium carbonate does not significantly impact the thickening properties of the system, indicating comparable shear resistance between the two systems.

3.4. Emulsifying Performance Evaluation of the Alkali-Free TC System.
The findings from the bottle test method demonstrate the water separation rate of the emulsion, as depicted in Figure 7. Specifically, the alkali-free TC system emulsion exhibited a water separation rate of 96% after 0.67 h and 100% after 1.0 h. Conversely, the weak base ternary system emulsion displayed a water separation rate of 92% after 0.67 h,
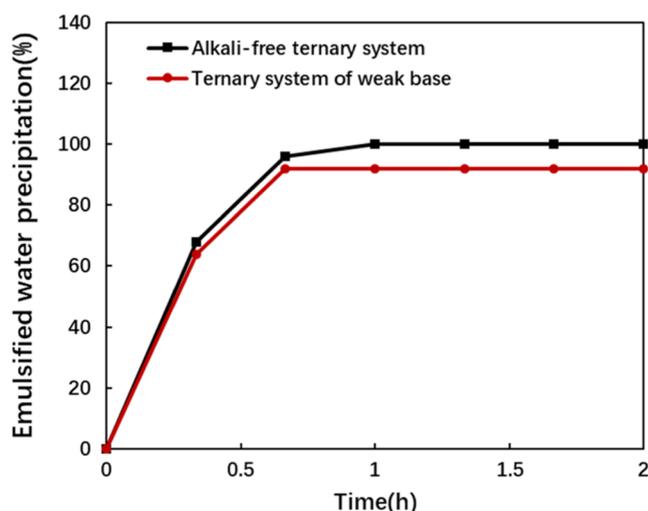
Figure 7. Emulsification water separation rate of the alkali-free TC and weak alkali ASP system.

and although it reached 92% after 2.0 h, it did not achieve complete separation. Hence, the emulsification efficacy of the alkali-free TC system is comparatively inferior to that of the weak alkali ASP system.

3.5. Corrosion Performance Evaluation of the Alkali-Free TC System.
Due to the corrosive effect of the inorganic salt on the metal, the $20^{\#}$ steel hanging piece was subjected to immersion in both the alkali-free TC system and the weak alkali ASP system. Subsequently, the Fe^{3+} content in the solution of both systems was determined after a 24-h period (Table 5). The experimental findings revealed that the

Table 5. Fe^{3+} Concentration after Soaking $20^{\#}$ Steel Modules in Different Flooding Systems

system	Fe^{3+} content before soaking (mg/L)	Fe^{3+} content after soaking (mg/L)
alkali-free TC system	0.61	1.65
weak alkali ASP system		0.65

concentration of free Fe^{3+} in the solution of the alkali-free ternary composite system increased from 0.61 to 1.65 mg/L, whereas the concentration of free Fe^{3+} in the solution of the weak alkali ternary composite system increased from 0.61 to 0.65 mg/L. When alkaline substances, such as Na_2CO_3, come into contact with $20^{\#}$ steel, passivation takes place, resulting in the formation of a passivation film on the surface of the hanging piece. This film reduces the corrosion caused by inorganic salts on the hanging piece. Additionally, sodium chloride enhances the conductivity of aqueous solutions and accelerates the electrochemical corrosion reaction of metals. Consequently, when implementing alkali-free TC systems in practical settings, it is crucial to consider the corrosion resistance of metals, such as pipelines.

3.6. Comprehensive Evaluation of Oil Displacement Performance of the Alkali-Free TC System.
The experiment involved conducting an oil displacement study on a 1D homogeneous Bailey core. The objective was to compare and analyze the oil displacement performance of an alkali-free TC system and a weakly alkali ASP system. Multiple parallel experiments were conducted for each scheme, and the findings are presented in Table 6. The experimental results indicate that within the range of core gas permeability of $(366-390) \times 10^{-3}$ μm^2, the injection method of using a 0.3 PV main slug of the ternary system, followed by a 0.2 PV polymer subsequent protective slug, was employed. The alkali-free TC system exhibits an average recovery rate that is 27.31% higher than that achieved through water flooding, while the weak alkali ASP system demonstrates a 29.87% higher average recovery rate compared to water flooding. Furthermore, during the chemical flooding stage, the average enhanced oil recovery of the alkali-free TC system is 2.56 percentage points lower than that of the weak alkali ASP system.

Figure 8a illustrates the correlation between the relative concentration of each component and the injection volume at the production end of the alkali-free TC system's chemical flooding stage. The findings indicate that the polymer encounters the agent within the range of 0.6 PV to 1.9 PV, the surfactant falls within the range of 1.1 PV to 1.9 PV, and the sodium chloride lies within the range of 0.7 PV to 1.9 PV. The order of the components is as follows: polymer, sodium chloride, and surfactant, with a difference of 0.5 PV between

Table 6. Oil Displacement Effect of Different ASP Flooding Systems

flooding system	parallel classes	gas permeability distribution and mean value ($\times 10^{-3}$ μm^2)	oil saturation distribution and mean value (%)	distribution and mean value of water flooding recovery (%)	distribution and mean value of chemical flooding recovery factor (%)	total recovery distribution and mean value (%)
alkali-free TC system	36	379−390	62.56−64.11	38.88−40.00	26.56−27.96	65.56−67.90
		383	63.71	39.52	27.31	66.83
weak alkali ASP system	31	366−378	62.97−64.05	38.05−39.82	29.02−30.12	67.12−69.85
		372	63.59	39.12	29.87	68.99

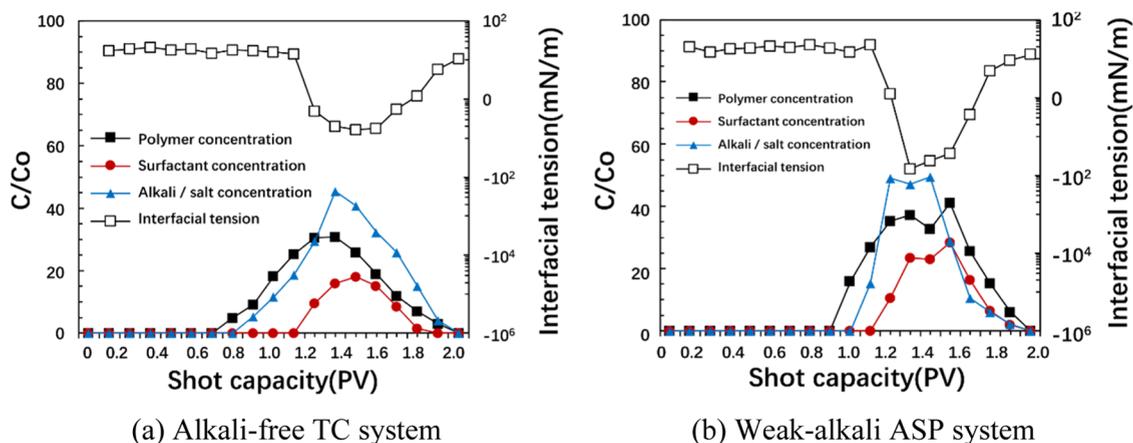(a) Alkali-free TC system   (b) Weak-alkali ASP system

Figure 8. Relationship between relative concentration of each component at the production end, interfacial tension, and injection volume during core flooding.
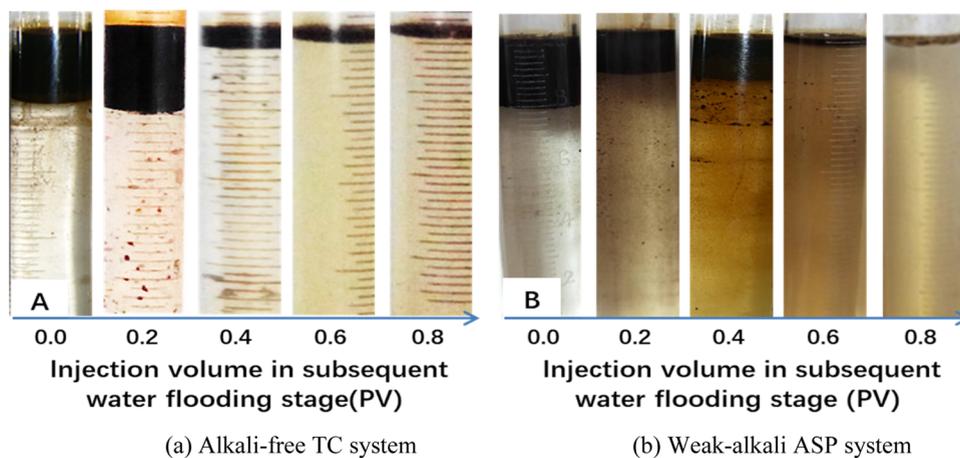

(a) Alkali-free TC system   (b) Weak-alkali ASP system

Figure 9. Emulsification of the produced fluid in subsequent chase water flooding of alkali-free TC and the weak alkali ASP system.

the polymer and the surfactant. During the period of maximum concentration, the polymer exhibits a value of 1.4 PV, the surfactant demonstrates a value of 1.5 PV, the sodium chloride displays a value of 1.4 PV, and the distribution of concentration peaks differs by only 0.1 PV.

The relationship between the relative concentration of each component at the extraction end and the injection amount during the chemical flooding stage of the weak alkaline ternary system is shown in Figure 8b. The findings indicate that the polymer exhibits a range of 1.0−1.9 PV, the surfactant falls within the range of 1.3−1.9 PV, the sodium carbonate is within the range of 1.1−1.9 PV, and there is a difference of 0.3 PV in the time of agent visibility. At the time of peak concentration, the polymer reaches 1.6 PV, the surfactant reaches 1.6 PV, the sodium carbonate reaches 1.2 PV, and there is a difference of 0.4 PV in the distribution of concentration peaks. Hence, the

two systems exhibit distinct chromatographic separation characteristics. The alkali-free TC system displays a significant disparity in the elution time of the analyte, while the discrepancy in the peak of the analyte is minimal. Conversely, the weak alkali ASP system demonstrates a minor divergence in the elution time of the analyte but a substantial difference in the peak of the analyte. Nevertheless, both systems manifest specific chromatographic separation phenomena with a comparable degree of chromatographic separation.

In the alkali-free TC system, the interfacial tension of the produced fluid decreases to a minimum value of 10^{-1} mN/m between 1.2 and 1.7 PV. While in the weak base ternary system, the interfacial tension of the produced fluid reaches its lowest value at 1.4 PV, measuring in the order of magnitude of 10^{-2} mN/m, but this low value is sustained for only 0.1 PV. The interfacial tension then increases to the order of 10^{-1} mN/

m between 1.5 and 1.7 PV. Hence, the alkali-free TC system exhibits the attributes of a slight reduction in interfacial tension of the resulting fluid, coupled with a prolonged period of sustained low values.

The emulsification phenomenon of the produced liquid in the core flooding experiment of the alkali-free TC system and the weak alkali ASP system was analyzed, and the findings are presented in Figure 9. It was observed that there was no significant emulsification phenomenon in the produced liquid of the alkali-free TC system during the subsequent water flooding stage. The weak alkali ASP system exhibits a pronounced emulsification phenomenon during the subsequent water flooding stage, particularly when the emulsification is concentrated in the subsequent water flooding, 0.4 PV.

In this case, oil production surpasses that of the alkali-free TC system at the same stage. Nevertheless, numerous experimental findings indicate that if the fluid produced at the outlet end of the core experiment is emulsified, the recovery rate is 5−6% higher compared to when it is unemulsified.[31,32] The disparity in enhanced oil recovery during the chemical flooding stage in the aforementioned displacement experiment is attributed to the variation in emulsification capability between the alkali-free TC system and the weakly alkali ASP system.

During the displacement process of the weak alkali ASP system, the Winsor II type is first formed in the high oil content stage, with an increase in viscosity, which plays a role in emulsifying and increasing viscosity, expanding the affected volume. At this time, the local pressure gradient during the oil displacement process is the highest and the injection pressure increases significantly. Afterward, Winsor type I phase characteristics are formed, with low viscosity and good flowability of the emulsion (Figure 10). While the emulsifying
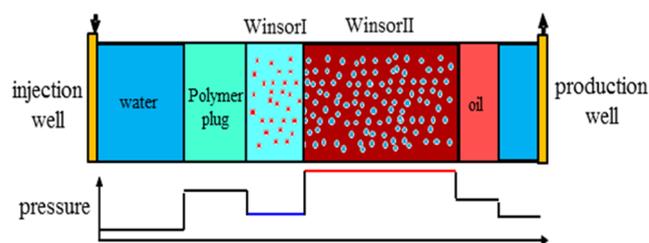
Figure 10. Schematic diagram of the phase transformation of the weak alkali ASP system.

ability of the alkali-free TC system is relatively weak, the next step of research would be to consider adding an E-surfactant to enhance the emulsification performance of the composite system.

3.7. Preliminary Benefit Evaluation of the Alkali-Free TC System.
In the assessment of the potential for popularization and application, a comprehensive evaluation of both agent cost and oil displacement effect can provide a more precise assessment of the prospects for implementing a chemical flooding system. The initial analysis of benefits for the two systems is presented in Table 7. Considering that the cost of industrial sodium chloride is only 25.5% of the cost of industrial sodium carbonate, the calculation of the unilateral oil displacement agent cost throughout the chemical flooding process is based on the outcomes of the oil displacement experiments. The alkali-free TC system is priced at 63.17 yuan/m^3, which is lower than the weak alkali ASP system priced at 80.85 yuan/m^3. The findings from comprehensive oil displacement experiments indicate that the alkali-free TC system enhances oil recovery by 27.31% compared with water flooding, while the weak alkali ASP system improves oil recovery by 29.87% compared with water flooding. Consequently, the cost of the alkali-free TC system is 17.02% lower than that of the weak alkali ASP system when calculating the cost of a single liquid per 1 percentage point increase in oil recovery.

In comparison to polymer flooding, the alkali-free TC system exhibits a 9.17% reduction in cost due to its significantly enhanced recovery rate. Additionally, the absence of alkalization in ASP flooding prevents scaling in the injection production system caused by alkali, thereby reducing the maintenance workload and operational expenses. Consequently, the alkali-free TC system presents favorable economic and social advantages, making it a promising prospect for application.

4. CONCLUSIONS

(1) Based on the feasibility analysis of alkali-free in the ternary composite oil displacement system, it is found through experiments that the viscosity increase, viscoelasticity, shear resistance, interfacial activity, and stability of alkali-free TC system are basically the same as those of the weak alkali ASP system.

(2) The average recovery rate of the alkali-free TC system is 27.31% higher than that of water flooding, and the average recovery rate during the chemical flooding stage is 2.56 percentage points lower than that of the weak alkali ASP system. Compared to the weak alkali ASP system, the chemical agent cost of the alkali-free TC system decreases by 17.02%.

(3) During the displacement process of the weak alkali ASP system, Winsor I and II emulsion has appeared, while there is no significant emulsification phenomenon in the

Table 7. Cost Data of Different Systems

| system types | improve the recovery efficiency (%) | main plug | | subsequent slug | | chemical flooding process | | for every 1 percentage point increase in recovery rate, the cost of single liquid is increased (RMB) |
		slug size (PV)	the cost of single liquid (RMB/m^3)	slug size (PV)	the cost of single liquid (RMB/m^3)	slug size (PV)	the cost of single liquid (RMB/m^3)	
polymers	10.89	0.5	27.50			0.5	27.50	2.525
alkali-free TC system	27.31	0.3	86.95	0.2	27.50	0.5	63.17	2.313
weak alkali ASP system	29.87	0.3	116.41	0.2	27.50	0.5	80.85	2.707

alkali-free TC system due to the lack of alkaline environmental conditions, the mutual solubility between petroleum sulfonates and crude oil becomes weaker. Therefore, the next step of research would be to consider adding an E-surfactant to enhance the emulsification performance of the composite system.

■ AUTHOR INFORMATION

Corresponding Author

Xiaoying Liu − Key Laboratory of Enhanced Oil Recovery of Education Ministry, Northeast Petroleum University, Daqing 163318, China; Email: cy8klxy123456@163.com

Authors

Hao Wu − PetroChina Daqing Oilfield Co., Ltd., Daqing 163002, China

Sian Chen − PetroChina Daqing Oilfield Co., Ltd., Daqing 163002, China

Jingang He − PetroChina Daqing Oilfield Co., Ltd., Daqing 163002, China

Zhao Yang − Key Laboratory of Enhanced Oil Recovery of Education Ministry, Northeast Petroleum University, Daqing 163318, China; PetroChina Daqing Oilfield Co., Ltd., Daqing 163002, China; orcid.org/0000-0003-0991-8689

Jiecheng Cheng − PetroChina Daqing Oilfield Co., Ltd., Daqing 163002, China

Jingchun Wu − Key Laboratory of Enhanced Oil Recovery of Education Ministry, Northeast Petroleum University, Daqing 163318, China

Complete contact information is available at:
https://pubs.acs.org/10.1021/acsomega.3c09527

Notes

The authors declare no competing financial interest.

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