

## New technology of anti-gas channeling for CO<sub>2</sub> flooding in heterogeneous tight oil reservoirs: construction and performance evaluation of small molecule thickening system with low interfacial tension

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### ABSTRACT

CO<sub>2</sub> flooding can improve crude oil recovery, and realize CO<sub>2</sub> underground storage, which is an important means to increase the recovery rate in tight reservoirs. CO<sub>2</sub>-water alternating flooding, which is a method to combine the advantages of CO<sub>2</sub> flooding and water flooding, has good applicability and is the most commonly used method in gas injection preventing channeling. However, due to the low viscosity of water medium under reservoir conditions, plugging ability for water to heterogeneous reservoirs is limited during CO<sub>2</sub>-water alternate flooding, and the oil displacement effect of CO<sub>2</sub> flooding needs to be further improved. Therefore, a low interfacial tension small molecule thickening system (DXZT) was constructed based on small molecule oligomeric organic active substances. When implementing alternative flooding with CO<sub>2</sub>, the DXZT has good injection performance and environmental adaptability in heterogeneous tight reservoirs, meeting the needs of improving the swept volume and oil washing efficiency of CO<sub>2</sub> flooding. In this paper, the interfacial activity, viscosity increasing, emulsification, wettability, foam properties and reservoir environmental adaptability of the DXZT were systematically evaluated. The injectivity and

preventing gas channeling effect of the CO<sub>2</sub> and DXZT alternating flooding were investigated, and the preventing CO<sub>2</sub> channeling mechanism of DXZT was analyzed. The results show that DXZT has good interfacial activity ( $\leq 0.02 \text{ mN/m}$ ), viscosity enhancing ( $2.0\text{-}15.4 \text{ mPa}\cdot\text{s}$ ), environmental adaptability of high salinity, high calcium ion and acidic CO<sub>2</sub> (salinity  $\leq 80000 \text{ mg/L}$ ,  $\text{Ca}^{2+} \leq 15400 \text{ mg/L}$ ,  $\text{pH} \geq 3$ ), oil-water emulsification, water wettability and foam performance (foam comprehensive index  $\geq 15443 \text{ mL}\cdot\text{min}$ ). CO<sub>2</sub> and DXZT alternate flooding has good injectivity for tight core ( $0.242 \text{ mD}$ ). After water flooding in heterogeneous tight cores, CO<sub>2</sub>-DXZT alternative flooding recovery increased by 14.8% than comprehensive water flooding recovery, which was better than single CO<sub>2</sub> flooding or DXZT flooding. With the increase of alternating drive rounds, the recovery rate of low permeability core and total comprehensive recovery rate are increasing. Which shows that DXZT has the ability to block the high permeability channel, divert CO<sub>2</sub> to the low permeability channel, start the remaining oil, and prevent CO<sub>2</sub> channeling in high permeability zone. The anti-gas channeling mechanism of DXZT includes: DXZT increases viscosity and has better mobility adjustment ability than water; is easy to

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inject high permeability channel or fracture, plug and seal these channelings, and form foam with CO<sub>2</sub> that has entered the channel, strengthen the sealing ability to high permeability channel. That is beneficial to the subsequent CO<sub>2</sub> divert, start the remaining oil in the low permeability channel and expand the swept volume of CO<sub>2</sub> flooding. Thus, DXZT is a new method and technology to prevent gas channeling in CO<sub>2</sub> flooding, which has broad application prospects in improving the recovery of CO<sub>2</sub> flooding in heterogeneous tight oil reservoirs.

**Keywords:** heterogeneous tight oil reservoirs; CO<sub>2</sub> flooding; small molecule tackifying system; Preventing gas channeling mechanism; New technology for preventing gas channeling.

## 1. INTRODUCTION

China's tight oil resources exceed  $100 \times 10^8$ t and have become an important guarantee for the country to increase its crude oil reserves and enhance oil production<sup>[1-2]</sup>. However, the tight oil reservoirs have poor reservoir properties, strong non-homogeneous, and low natural production capacity, thus, it is necessary to reduce reservoir densification degree and increase its production energy to improve the tight oil reservoir recovery<sup>[3-5]</sup>. CO<sub>2</sub> flooding is an effective method to improve the energy and recovery efficiency of tight oil reservoirs, and also is an environmental technical measure to implement CO<sub>2</sub> storage. Unfortunately, improving recovery effect of CO<sub>2</sub> flooding is unsharp in heterogeneous tight oil reservoir, because viscosity of supercritical CO<sub>2</sub> is lower and viscous fingering and gas channeling are serious in CO<sub>2</sub> flooding<sup>[8-9]</sup>.

In view of this, experts and scholars have explored techniques such as water-gas alternation, foam, gel and organic small molecule amine to seal the fracture, retard gas channeling and improve the suction gas profile. Among them, water-gas alternation technology is highly operable and most commonly used in gas injection projects, but the plugging effect of water is not obvious under higher permeability difference or stronger heterogeneous condition and the oil displacement effect needs to be further improved<sup>[10-12]</sup>. CO<sub>2</sub> foam has higher apparent viscosity and can seal the high permeability channels in the formation through the Jamin effect, effectively improve CO<sub>2</sub> mobility control, but the

mechanism of CO<sub>2</sub> foam occurring, migrating, breaking" and its controlling factors at the microscopic scale are still unclear due to CO<sub>2</sub> foam is a thermodynamically unstable system<sup>[13]</sup>, moreover, the ability for the conventional CO<sub>2</sub> foam to adjust anisotropism and resist temperature and salt all need to be improved<sup>[14]</sup>. The polymer gel has better plugging properties for fractured tight reservoirs ( $\geq 0.1$  mD). However, the gelation time of such gels is longer, easy to block near-well zone and can damage oil reservoir, and has poor long-term stability in an acidic CO<sub>2</sub> environment<sup>[15-17]</sup>. The reaction product of organic small molecule amine and CO<sub>2</sub> can effectively plug the high permeability channel, but it usually need to combine with polymer gel to implement two-stage blocking, and small molecule amine is easy to volatilize and emit irritating odor, has the risk of environmental pollution<sup>[18]</sup>. Therefore, it is urgent to develop a novel preventing gas channeling system of the CO<sub>2</sub> flooding that meets requirements of easily injecting and effectively adjusting heterogeneity in the tight oil reservoir, in order to drastically improve CO<sub>2</sub> flooding recovery and CO<sub>2</sub> storage rate.

In this paper, a low interfacial tension small-molecule viscosity increasing system (DXZT) was developed by small-molecule oligomeric organic active substances. Then, the interfacial activity, viscosity increasing, emulsification, wettability, foam performance, reservoir environment adaptability, injectivity and preventing gas channeling effect of DXZT are systematically evaluated, finally, the mechanisms of DXZT preventing CO<sub>2</sub> gas channeling are discussed. These studies provide new ideas and experimental basis for CO<sub>2</sub> flooding gas channeling prevention technology in tight reservoirs.

## 2. EXPERIMENTAL SECTION

### 2.1 Materials and Instruments

Experimental materials: NaCl, Na<sub>2</sub>SO<sub>4</sub>, NaHCO<sub>3</sub>, CaCl<sub>2</sub>, MgCl<sub>2</sub>·6H<sub>2</sub>O, KCl purchased in Shanghai Aladdin Biochemical Technology Co., Ltd.; Low interfacial tension small molecule tackifier, belongs to oligomer (n=2-5) small molecule active organic matter, containing hydroxyl, carboxyl, sulfonic group and hydrocarbon chain, provided by the School of Petroleum Engineering, Yangtze University; CO<sub>2</sub> with a volume fraction of 99.99% was purchased from Hunan Yuanchuang Gas Co., Ltd.; Sudan red and methylene blue were purchased from Shenyang Sinoda Biotechnology Co., Ltd.; Kerosene and white oil were purchased from Wuhan Yicaiyang Technology Co., Ltd.; The crude oil samples were

provided by Yanchang Oilfield, and the density and viscosity of crude oil at a reservoir temperature of 47.2°C were 0.83g/cm<sup>3</sup> and 3.4mPa·s respectively; Test core is a natural core, with a length of 5.00-7.00cm, a diameter of 2.50cm, and a gas permeability: 0.173-0.824mD.

Experimental instruments: Brookfield DV2T viscometer, Brookfield Company, USA; TEXAS-500 Rotary Drop Interfacial Tensiometer, Kono Industries, USA; OCA 50 Automatic Contact Angle Measuring Instrument, Dataphysics, Germany; Heterogeneous microscopic etching model, which opens diagonally, geometric dimensions of 75mm×75mm, effective etching area of 45mm×45mm, Zhenjiang Huarui Chip Technology Co., Ltd.; Core displacement experimental device, mainly including double-cylinder constant speed and constant pressure displacement pump, core gripper, return pressure valve, piston intermediate vessel, pressure sensor, etc., Changzhou Zhongbei Instrument Co., Ltd.

## 2.2 Experimental methods

### 2.2.1 Solution preparation

Preparation of simulated injection water and formation water : NaCl, Na<sub>2</sub>SO<sub>4</sub>, NaHCO<sub>3</sub>, CaCl<sub>2</sub>, MgCl<sub>2</sub> · 6H<sub>2</sub>O and KCl were weighed and added to distilled water in turn, and stirred to completely dissolve. The simulated injection water with a salinity of 6788.23 mg/L and the simulated formation water with a salinity of 80000 mg/L were prepared and were constant volume in a 2L volumetric flask for later use. The ion type and composition of simulated water are shown in Table 1.

Table 1 Simulated ion composition of injected water and formation water

Water type	Ion concentration (mg/L).							mineralization (mg/L).
	Na <sup>+</sup>	K <sup>+</sup>	Ca <sup>2+</sup>	Mg <sup>2+</sup>	Cl <sup>-</sup>	SO <sub>4</sub> <sup>2-</sup>	HCO <sub>3</sub> <sup>-</sup>	
Injected water	168 4.33	10. 67	349 .74	75. 01	103 3.48	347 0.9	164 .1	6788.23
Formation water	951 3.6	29 2.2	154 00	56. 8	543 35.2	301 .8	100 .4	80000

Preparation of low interfacial tension small molecule tackifier solution: 18.0g low interfacial tension small molecule tackifier was accurately weighed and placed in a beaker filled with simulated injected water, and mechanically stirred for 4h. After being completely dissolved, it was transferred into a 500 mL volumetric flask to constant volume to prepare a high concentration low interfacial tension small molecule tackifier solution. The low concentration test solution is diluted by the high concentration solution.

Visualization experimental water: the injected water is stained with methylene blue and filtered for later use.

Visualize the experimental oil: according to the viscosity required for the experiment, simulated oil was prepared by compounding the kerosene and white oil in a certain proportion, and then was dyed with Sudan red and was filtered for later use.

### 2.2.2 Interfacial activity, viscosity, wettability, emulsification and foam performance tests

(1) Oil-water interfacial tension test: The interfacial tension between solution and crude oil was measured by TEXAS-500 rotary drop interfacial tension meter at 47.2 ° C and 5000 r/min.

(2) Viscosity test: The Brookfield DV 2T viscometer was used to test the viscosity of the solution under the condition of temperature 47.2°C and shear rate 7s<sup>-1</sup>. The error range of the viscosity was 1mPa·s ± 0.005mPa·s.

(3) Wettability test: The core was dried and cut into core slices with the same diameter and thickness. The core slices were immersed in low interfacial tension small molecule viscosifying system (DXZT) and CO<sub>2</sub>-low interfacial tension small molecule viscosifying system (CO<sub>2</sub>-DXZT) for 6h, then, the core slices were taken out and dried naturally. The OCA 50 automatic contact angle measuring instrument was used to measure the contact angle θ of water phase/oil phase on the surface of core thin section, and the wettability change of core surface after different fluid immersion was judged by θ value.

(4) Emulsification test: First, the low interfacial tension thickening system (DXZT) and dehydrated crude oil were added to a 50 mL measuring cylinder at a certain volume ratio, and shaken up and down for 100 times to make the two mixed evenly. Then the mixed oil-water emulsion was placed in a constant temperature water bath at 47.2°C, and the emulsion stability time was observed and recorded.

(5) Foam performance test: turn on the Roche foam meter, set the temperature to 47.2°C, and make the liquid to be measured flows from a height of 450mm to the surface of the same liquid (50 mL) and forms foam, measuring the resulting foam volume and foam half-life.

### 2.2.3 Core injection experiment

According to the permeability range of tight reservoirs, a natural core with a permeability of 0.242mD was selected. The injectivity of alternating injection of CO<sub>2</sub>-low interfacial tension small molecule viscosifying system (DXZT) was evaluated under reservoir temperature conditions.

## 2.2.4 Double-pipe natural core oil displacement experiment

At 47.2°C, the formation heterogeneity permeability contrast 4.3 ( 0.756mD/ 0.173mD and 0.824mD / 0.191mD ) was simulated, and water flooding was carried out by constant pressure displacement until the water content of the produced liquid at the core outlet reached 90%. Subsequently, continuous CO<sub>2</sub> flooding, low interfacial tension small molecule viscosifier system (DXZT)-CO<sub>2</sub> alternate flooding were carried out to compare the oil displacement efficiency under the two displacement methods.

## 2.2.5 Microscopic visualization model oil displacement experiment

The heterogeneous micro-etching model was used to visually observe the start-up of remaining oil when the low interfacial tension small molecule viscosifying system was injected after water flooding. Firstly, the heterogeneous microscopic model was vacuumized to saturate the simulated oil (red) until the model was completely filled with oil. Secondly, the core flooding process was simulated. Water flooding (blue) was carried out at a constant speed until the oil was no longer produced at the outlet of the model. The experimental process images were recorded by computer and video equipment. Finally, a certain amount of low interfacial tension small molecule viscosifier DXZT (undyed) was injected at a constant speed, and the remaining oil start-up changes during the displacement process were recorded until the outlet end was no longer out of oil and the experiment was stopped.

## 3. RESULTS AND DISCUSSION

### 3.1 Construction of low interfacial tension small molecule viscosity increasing system

#### 3.1.1 Effect of the amount of low interfacial tension small molecule tackifier on interfacial activity

At test temperature 47.2 °C, salinity 6788.23mg/L, the interfacial tension between different mass fractions low interfacial tension small molecule tackifier solution and crude oil changes is shown in Figure 1.

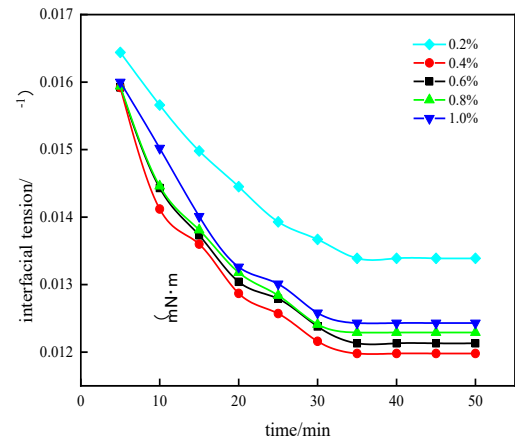


Figure 1. Oil-water interfacial tension curve of low interfacial tension small molecule tackifier with its mass fraction

As can be seen from Figure 1, dynamic equilibrium interfacial tension shows a trend of firstly decreasing and then slowly increasing with the enhancement of mass fraction of low interfacial tension small molecule viscosity enhancer solution. The oil-water interfacial tension indicates the lowest ( $1.7 \times 10^{-2}$  mN/m) as the mass fraction is 0.4%. Because low interfacial tension small molecule viscosity enhancers contain multiple hydrophilic groups (carboxyl, hydroxyl, sulfonic acid groups) and hydrophobic group (chain hydrocarbons), and is similar to Gemini surfactants, only has a relatively higher degree of polymerization ( $n=3-5$ ). and it can form hydrogen bonding with water and hydrophobic association bonding with crude oil, can be more quickly and better adsorbing on the oil-water interface, effectively reduce the oil-water interfacial tension<sup>[19]</sup>. The oil-water interfacial tension was lower than  $2 \times 10^{-2}$  mN/m in the mass fraction range of 0.2%-1.0%, indicating that the low interfacial tension small molecule viscosity enhancers do have the ability to reduce the oil-water interfacial tension to low interfacial tension range ( $10^{-2}$  mN/m), and have good potential to start reservoir residual oil in the experimental dosage range.

#### 3.1.2 Effect of low interfacial tension small molecule tackifier dosage on its viscosity

The influence of different mass fractions on the viscosity of low interfacial tension small molecule tackifier solution is shown in Figure 2 at a temperature of 47.2°C and a salinity of 6788.23mg/L.

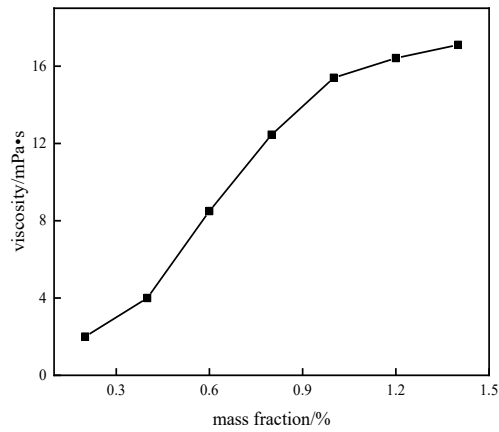


Figure 2. Effect of mass fraction on viscosity of low interfacial tension small molecule tackifier solution

It can be seen from Figure 2 that the viscosity of low interfacial tension small molecule tackifier solution increases with the increase of mass fraction. At a mass fraction of 0.4%, the viscosity has reached 4.0 mPa·s; while the mass fraction continue to increase to 0.8% and 1.0%, the viscosity of the system also increased fleetly to 12.45mPa·s and 15.4mPa·s. The analysis believes that this is mainly related to the hydrophobic association between molecules. As the mass fraction of the system increases, the intermolecular hydrophobic association increases, and a large number of molecules aggregate to form a large physical overlapping dynamic network structure<sup>[20]</sup>, resulting in a sharp increase in viscosity of low interfacial tension small molecule tackifying systems. However, considering the compactness of the reservoir, when the viscosity of the system is too high, its injectability may be poor. When the viscosity is similar to that of formation oil, the low interfacial tension and small molecule viscosifier is suitable.

Combined with the above interfacial tension data results, it is found that the 0.4% low interfacial tension small molecule tackifier solution not only has low interfacial tension, but also has a similar viscosity to formation crude oil, and has a good oil-water flow ratio. Therefore, a low interfacial tension small molecule viscosity system was constructed from 0.4% low interfacial tension small molecule tackifier solution, abbreviated: DXZT.

### 3.2 Performance of DXZT

#### 3.2.1 The interfacial activity and viscosity of DXZT

The interfacial activity and viscosity of DXZT at a fixed temperature of 47.2°C and a salinity degree of 6788.23mg/L are shown in Table 2.

Table 2. The interfacial activity and viscosity of DXZT

system	Oil-water interfacial tension (mN/m)	Viscosity (mPa·s)
m		

It can be seen from Table 2 that DXZT has both low interfacial tension and slightly higher viscosity than crude oil. It is an oil displacement agent with good interfacial activity and viscosity.

#### 3.2.2 Emulsifying properties of DXZT

At 47.2 °C, the stability time of emulsion formed by DXZT and crude oil with different oil-water ratios is shown in Figure 3.

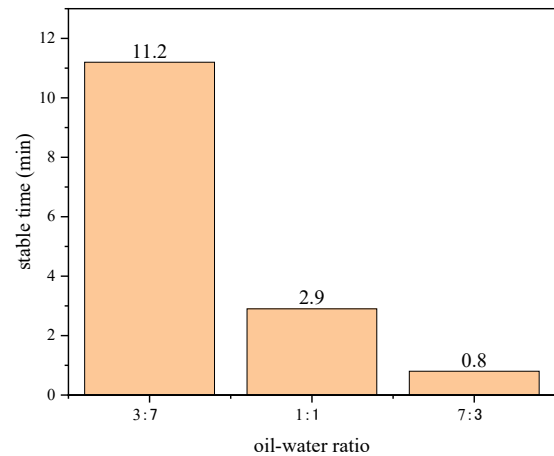


Figure 3. The histogram of emulsion stability of different crude oil DXZT solution ratio

It can be seen from Fig.3 that DXZT and crude oil can emulsify and form oil-water emulsion under different oil-water ratio conditions (3:7,1:1,7:3 ). The stability time of emulsion decreased with the increase of oil-water ratio, indicating that the stability of emulsion formed by DXZT and crude oil was related to oil-water ratio. However, which also directly verified that DXZT had ability to emulsify formation residual oils.

#### 3.2.3 Wettability of DXZT

The change of contact angle of natural core surface after DXZT and CO<sub>2</sub>-DXZT treatment is shown in Figure 4.

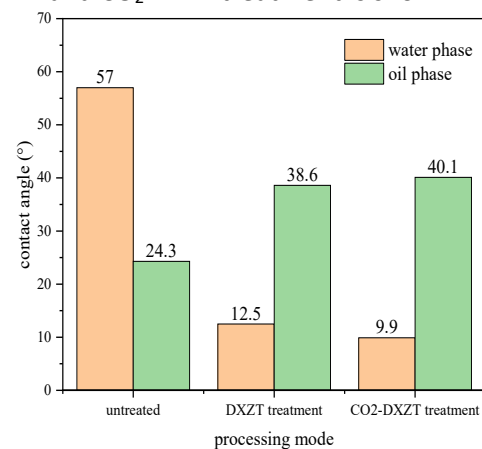


Figure 4. The change of contact angle of natural core surface before and after DXZT treatment

After DXZT treatment, the water-phase contact angle of the rock surface decreased from 57.0° to 12.5°, and the hydrophilicity of the rock was enhanced. The contact angle of the oil phase increased from 24.3° to 38.6°, the rock surface was more oleophobic, and the wettability of the rock surface changed to hydrophilic. After CO<sup>2</sup>-DXZT treatment, the water-phase contact angle is further reduced to 9.9°, and the oil-phase contact angle is further increased to 40.1°. Enhanced hydrophilic wettability of the rock surface. This change is beneficial to the initiation and peeling of the remaining oil, which in turn makes the flow pore size relatively larger, and because the water phase is more likely to invade the hydrophilic layer, it can improve the injection of the displacement phase, with the effect of depressurization and injection [21-22].

### 3.2.4 Foam properties of DXZT

Consider that when CO<sub>2</sub> is fully dissolved in the formation water, it will cause the formation water to carbonify, thereby reducing the pH of DXZT. Under stratigraphic conditions, the pH value of DXZT dropped to 3.4 after fully dissolving CO<sub>2</sub>. Therefore, the foam properties of DXZT at 47.2°C and pH values of 3.4 and 7.5 were investigated. The results are shown in Table 3.

Table 3. Foam properties of DXZT

Mineralization/ mg. L <sup>-1</sup>	pH	Temperature/ °C	Initial foam volume/mL	Half-life/min	Foam Composite Index/mL·min
6788	7.5	47.2	140	128	13440
6788	3.4	47.2	145	142	15442.5

DXZT has good foaming performance and excellent foam stability, the half-life is higher than 2 hours, and the pH of water medium has little effect on the foam performance. The foam formed at low pH (pH=3.4) is more stable, and its foam composite index has reached 15442.5mL·min, belongs to the strong foam system. The field application shows that the foam comprehensive index ≥ 5000mL·min can meet the plugging requirements.

### 3.3 Environmental adaptability of DXZT

#### 3.3.1 The influence of salinity on the performance of DXZT

##### 3.3.1.1 Interfacial tension

At 47.2°C, the effect of mineralization change on the interfacial tension of DXZT is shown in Figure 5.

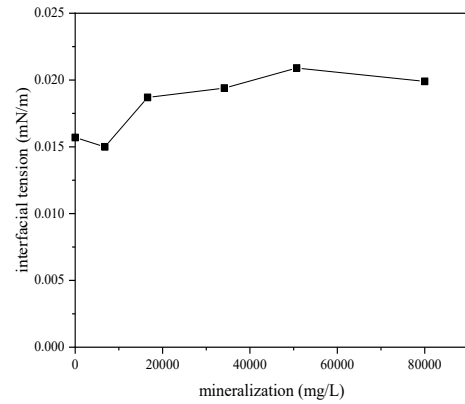


Figure 5. Effect of mineralization on DXZT interfacial tension

It can be seen from Figure 5 that when the mineralization is 0-80000mg/L, the oil-water interfacial tension of DXZT is always in the range of 0.015-0.021mN/m, and always maintains in the category of low interfacial tension. In general, the interfacial activity of DXZT is less affected by mineralization.

##### 3.3.1.2 Viscosity

At 47.2°C, the effect of mineralization on DXZT viscosity is shown in Figure 6.

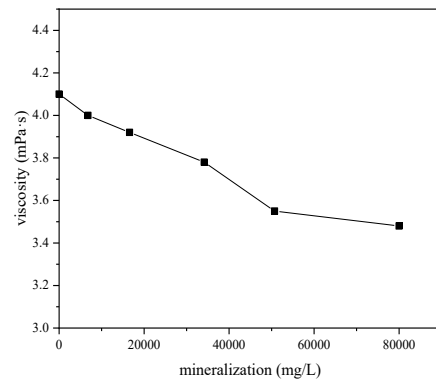


Figure 6. Effect of mineralization on viscosity of DXZT

As shown in Figure 6, with the increase of mineralization degree, the viscosity of DXZT shows a decreasing trend. When the mineralization degree increases from 0 to 80000mg/L, the viscosity decreases from 4.1mPa·s to 3.48mPa·s, with a decrease of 15.12%. The analysis shows that the high salinity will destroy the special network structure formed by DXZT and reduce the viscosity of the system. However, when the salinity is as high as 80000 mg/L, its viscosity is still 3.48 mPa·s. It can be seen that the viscosity of DXZT is less affected by the change of salinity, which shows good salinity adaptability.

##### 3.3.1.3 Emulsifying property

At 47.2 °C, the effect of mineralization change on the emulsification performance of DXZT ( oil-water ratio 3:7 ) is shown in table 4.

Table 4. Effect of mineralization on emulsifying properties of DXZT

Mineralization (mg/L)	Stable time (min)
6788	11.2
10182	8.3
13576	6.1
16970	3.2
20364	2.1

It can be seen from Table 4 that with the increase of salinity, the stability time of the emulsion is gradually shortened. This is because the increase of salinity enhances the flocculation and coalescence of the emulsion, which reduces the strength of the interfacial film, the coalescence resistance of the emulsion and the stability [23].

### 3.3.1.4 Foam properties

At 47.2°C, the effect of mineralization changes on DXZT foam properties is shown in Table 5.

Table 5 Effect of mineralization on DXZT foam performance

Mineralization/ mg. L <sup>-1</sup>	pH	Temperature/°C	Initial foam volume/ mL	Half-life/ min	Foam Composite Index/mL·min
6788	7.5	47.2	140	128	13440
	3.4	47.2	145	142	15442.5
40000	7.5	47.2	142	74	7881
	3.4	47.2	138	93	9625.5

From Table 5, it can be seen that under the influence of high salinity, DXZT has basically no effect on the foaming height under the condition of formation temperature, while the half-life attenuation is obvious and the foam stability becomes worse, but the half-life is still 74 min, and it still belongs to the strong foam system. Overall, it still has good foam stability.

In summary, DXZT has good adaptability to mineralization, and still has good interface activity, viscosity stability, emulsification and foam properties at high salinity, indicating that the oil displacement system has good salt resistance.

### 3.3.2. Effect of solution pH on the properties of DXZT

In the process of CO<sub>2</sub>-DXZT alternating flooding, CO<sub>2</sub> is fully dissolved in formation water, which will lead to the carbonation of formation water, thus reducing the pH value of DXZT. The decrease of pH value will cause the change of interfacial tension and viscosity of the system. At 47.2°C, the effect of pH value on the interfacial tension and viscosity of DXZT system is shown in Figure 7.

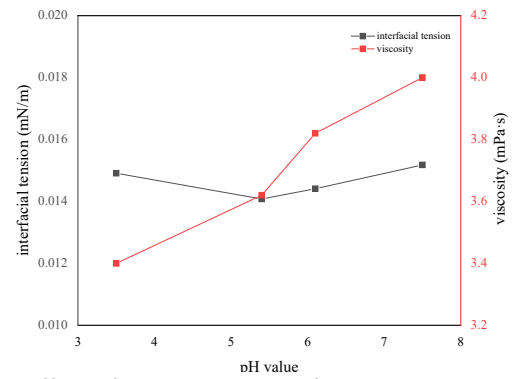


Figure 7. Effect of pH value on interfacial tension and viscosity of DXZT

It can be seen from figure 7 that the interfacial tension of DXZT can still maintain the order of 10<sup>-2</sup>mN/m at a lower pH value. It can be seen that the interfacial tension of the system is not affected by the pH value, and it still has the ability to emulsify the remaining oil of the reservoir. The viscosity of DXZT decreases with the decrease of pH value, from 7.5 to 3.5, and the viscosity from 4.0mPa·s It drops to 3.4 mPa·s and the viscosity decreases by 15%, so DXZT remains under weakly acidic conditions It has good viscosity stability.

### 3.4 CO<sub>2</sub>-DXZT alternating injection

The feasibility of CO<sub>2</sub>-DXZT alternating injection into tight cores ( 0.242mD ) was evaluated at reservoir temperature of 47.2°C. The experimental results are shown in Figure 8.

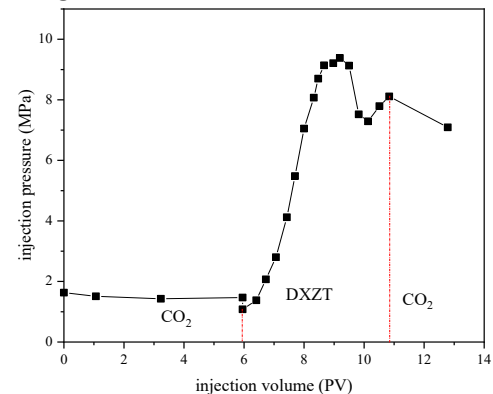


Figure 8. Alternating injection of CO<sub>2</sub>-DXZT in rock core with permeability of 0.242 mD

It can be seen from Figure 8 that when CO<sub>2</sub>-DXZT is alternately injected in the core with permeability Kg=0.242mD, the CO<sub>2</sub> displacement pressure difference is stable at 1.47MPa; After alternating injection of DXZT, the pressure begins to gradually increase, up to 9.38MPa, then stabilizes and declines somewhat; Finally, CO<sub>2</sub> was injected alternately, and with the increase of injection volumes, the injection pressure difference showed a downward trend, and at the end, the pressure difference was still higher than the initial CO<sub>2</sub> injection pressure

difference. However, in terms of the whole CO<sub>2</sub>-DXZT large-section plug and long-cycle alternating injection process, although the core permeability is extremely low (Kg=0.242mD), the injection pressure and pressure difference are relatively high (especially after injecting DXZT, the maximum pressure difference reaches 8.3MPa). However, there was no continuous increase in injection pressure or core plugging during the injection process, indicating the good feasibility of CO<sub>2</sub>-DXZT alternating injection..

### 3.5 Double-pipe core oil displacement effect

The evaluation results of the oil displacement effect of the double-pipe core are shown in Table 6.

Table 6 Oil displacement effect of double-pipe core

Displacement mode	Kg/mD	Water flooding recovery rate/%			Enhanced oil recovery/%		
		low permeability	High permeability	Comprehensive	low permeability	High permeability	Comprehensive
CO <sub>2</sub> flooding	0.173 0.756	20.77	50.15	37.22	21.34	51.98	38.49
0.3PV DXZT-CO <sub>2</sub> alternating flooding	0.191	25.14	49.77	38.44	49.92	56.1	53.26

It can be seen from Table 6 that after the water flooding to 90% water content of the output liquid, conducting continuous CO<sub>2</sub> flooding effect is no better and its comprehensive recovery rate is only higher than 1.27% that of continuous water flooding, especially, recovery of low permeability tube core only enhances 0.57% ,being less than 1.83% of high permeability tube core. Because CO<sub>2</sub> flooding is prone to flow along preferential seepage channels (high permeability channel), resulting in CO<sub>2</sub> is easier to break through and has smaller sweep volume. Surprisingly, the comprehensive recovery factor of CO<sub>2</sub>-DXZT alternate flooding is 14.82% higher than that of continuous water flooding, enhances also 14.77% higher than that of continuous CO<sub>2</sub> flooding after water flooding. Noteworthy, compared with CO<sub>2</sub> flooding, CO<sub>2</sub>-DXZT alternating flooding can significantly improve the core recovery of low permeability pipe by 28.58%, while the core recovery of high permeability pipe only enhanced by 4.12%. Which shows that DXZT can preferentially enter the hyperpermeability channel, and migrate and block them, then shunt subsequent CO<sub>2</sub> to the low-permeability channel, obviously improve the swept volume of CO<sub>2</sub> flooding and oil washing efficiency.

The effect of round times of CO<sub>2</sub>-DXZT alternating flooding on enhanced oil recovery was shown in Table 7. From Table 7, in first round of alternating flooding, the EOR of the high permeability pipe core was only 2.31%, while the EOR of the low permeability pipe core was

12.15%, and the EOR of the low permeability pipe core was more remarkable. In the second round, the EOR of the low permeability pipe core further increased 9.39%, and the EOR of the core of the high permeability pipe core also improved 2.43%. In the third round, the enhanced recovery was still obvious, and the recovery rate of the high/low permeability pipe core increased by 1.59% and 3.24% respectively. That means CO<sub>2</sub>-DXZT alternating flooding can not only solve the gas channeling problem of CO<sub>2</sub> flooding in heterogeneous tight oil reservoirs, but also can be conducted more than 3 times.

Table 7. Effect of DXZT-CO<sub>2</sub> alternating drive cycles on enhanced water flooding recovery

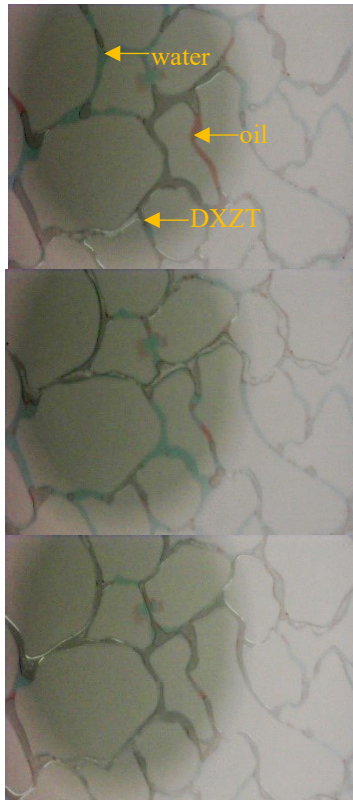
Displacement mode	Kg/mD	Water flooding recovery/%			EOR/(1 round).			EOR/(2 rounds).			EOR/(3 rounds).		
		Low permeability	High permeability	comprehensive	Low permeability	High permeability	comprehensive	Low permeability	High permeability	comprehensive	Low permeability	High permeability	comprehensive
0.3 PV DXZT-CO <sub>2</sub> alternating flooding	0.191	25.14	49.77	38.55	12.15	2.31	6.84	9.39	2.43	5.63	3.24	1.59	2.35

### 3.6 Gas channeling prevention of DXZT

#### 3.6.1 DXZT plugging effect

The plugging effect of DXZT is shown in Figure 9. DXZT aggregates with each other to form fluid columns, and the clusters exhibit good flow deformation ability, which can be deformed with pore scale changes (Figure 9-a), when DXZT aggregates deform through the pores. It will have a blocking effect on the pores, and it can only be deformed and passed through when a certain displacement pressure is reached, which can force the displacement fluid into a relatively low permeable channel and expand the ripple volume; And due to its own good transfer deformation ability, it will continue to block and deform through the aperture during the migration process (Figure 9-b), and then effectively adjust the oil displacement profile, and there is no obvious remaining oil in the pores of the characteristic points (Figure 9-c), reflecting DXZT has a larger ripple volume and higher oil displacement efficiency than water flooding.





(a) The thickening system enters the channel in the form of slug (b) The thickening system deforms through the pores (c) Displace the remaining oil encountered  
Figure 9. Effect of the blocking effect of DXZT

### 3.6.2 Form CO<sub>2</sub> foam to enhance the sealing ability of hypertonic channels

DXZT has good foam properties and can react with CO<sub>2</sub> to form foam, and bubble output can be observed from the outlet end during the DXZT-CO<sub>2</sub> alternating driving process. Under the formation temperature and pressure (47.2°C, 8.9 MPa), DXZT and supercritical CO<sub>2</sub> can form a large amount of foam after mixing in a visual reactor. The blistering volume is up to 960 mL (Figure 10) and the half-life is up to 13h, indicating DXZT is mixed with supercritical CO<sub>2</sub>, the foaming performance and stability of the foam are improved accordingly, and it has the potential to flow in porous media and effectively block high permeability layers or large pores for a long time. In the seepage channel, the formation of CO<sub>2</sub>-DXZT foam helps to strengthen the plugging and shunting effect of DXZT.



Figure 10. CO<sub>2</sub>-DXZT initial foam volume

In addition, considering that CO<sub>2</sub> will dissolve and extract crude oil in the reservoir during CO<sub>2</sub> flooding, the deposition of heavy hydrocarbons or colloidal asphaltenes after CO<sub>2</sub> flooding is serious, resulting in damage to the permeability of the reservoir, which greatly affects the effect of enhanced oil recovery in the later stage of CO<sub>2</sub> flooding<sup>[24-25]</sup>. In the process of DXZT-CO<sub>2</sub> alternate flooding, it has a hydrophilic wetting effect on the pore wall of the reservoir, which will lead to the weakening of the adhesion ability of heavy hydrocarbons such as asphalt to the pore wall. The high interfacial activity of DXZT makes it have good ability to emulsify hydrocarbon components, and the effect of emulsifying and dispersing crude oil is good, which is helpful to realize the displacement and recovery of all components of remaining oil. Using DXZT-CO<sub>2</sub> alternating flooding, the oil displacement efficiency can be effectively improved through DXZT's self-viscosity, high interface activity and wettability DXZT forms foam with CO<sub>2</sub>, which strengthens the sealing ability of the hyperosmotic channel, which is conducive to the subsequent CO<sub>2</sub> shunt to start the residual oil of the hypotonic channel and expand CO<sub>2</sub> drives the volume of the impact. It can be seen that DXZT-CO<sub>2</sub> alternating flooding has excellent potential application prospects in the anti-channeling of CO<sub>2</sub> flooding in tight reservoirs.

## 4. CONCLUSION

(1) This paper proposes a new idea of alternative flooding of CO<sub>2</sub>-low interfacial tension small molecule viscosity enhancement system to enhance oil recovery. The small molecule viscosity enhancement system can make the interfacial tension reach 10<sup>-2</sup>mN/m at a low mass fraction (0.4%), the viscosity is close to the viscosity of oil reservoir, and has good hydrophilic wetness, foam property and salt resistance.

(2) After water flooding reaches 90%, DXZT-CO<sub>2</sub> alternate flooding was transferred, and it can increase the integrated recovery factor by 14.82%, far higher than that of continuous CO<sub>2</sub> flooding comprehensive recovery (1.27%). In addition, the increase of core recovery efficiency of low permeability pipe will decrease accordingly with the increase of alternate rounds. DXZT-CO<sub>2</sub> alternating flooding can solve the problem of CO<sub>2</sub> gas channeling in heterogeneous tight reservoirs to a certain extent.

(3) DXZT selectively enters the hyperpermeability channel during formation migration to effectively block the hyperpermeable channel. Microscopic visual oil displacement experiments show that DXZT has good ability to deform and fill any pore morphology, and has better flow control and oil washing ability than water flooding.

(4) The mechanism of DXZT-CO<sub>2</sub> alternating drive against gas channeling includes DXZT's own stickiness, adjusting ability is superior to the mobility of water; It is easy to inject the hyperpermeability channel or crack for sealing and channeling, and the channel has been jacked into CO<sub>2</sub> to form foam, strengthening the hyperpermeability channel channeling capacity; It is conducive to the subsequent CO<sub>2</sub> diversion to start the remaining oil in the low permeability channel and expand the swept volume of CO<sub>2</sub> flooding. DXZT-CO<sub>2</sub> alternate flooding has excellent potential applications in tight oil reservoir development.

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## DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

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