

Article

Study on Enhanced Oil Recovery and Microscopic Mechanisms in Low-Permeability Reservoirs Using Nano-SiO₂/CTAB System

Tingting Cheng ¹, Jinyi Wang ¹, Huaizhu Liu ^{2,*} , Jun Ding ¹, Yuting Ren ¹ and Xinhao Gong ¹

¹ College of Petroleum Engineering, Chongqing University of Science and Technology, Chongqing 401331, China; 2020014@cqust.edu.cn (T.C.); 2025201137@cqust.edu.cn (J.W.); 2023201069@cqust.edu.cn (J.D.); 2024201056@cqust.edu.cn (Y.R.); 2024201058@cqust.edu.cn (X.G.)

² Tangshan Jiyou Ruifeng Chemical Limited Company, Jidong Oilfield, PetroChina, Tangshan 063200, China

* Correspondence: liuhuaizhu007@126.com

Abstract

In the field of enhanced oil recovery in low-permeability reservoirs, the application of nanomaterials has attracted widespread attention. However, conventional nanomaterials exhibit issues such as large particle size and poor dispersion stability. This study selected SiO₂ nanoparticles with a particle size of 10 nm and combined them with 12 types of commonly used oilfield surfactants. After aging at 120 °C for 48 h, using dispersion stability and interfacial tension (IFT) as evaluation criteria, hexadecyltrimethylammonium bromide (CTAB) was ultimately identified as the optimal modifier. The structure and morphology of the SiO₂ particles were characterized in detail using X-ray diffraction (XRD), Fourier-transform infrared spectroscopy (FT-IR), and transmission electron microscopy (TEM). The system evaluated the dispersion stability of nanofluids before and after modification, as well as the interfacial properties (IFT reduced to the 10^{−1} mN/m range) and wettability (oil-wet surfaces reversed to strongly water-wet, with contact angles decreasing to 30°) of nanofluids with different modification degrees. Considering economic factors, the modified nano-SiO₂ system with a ratio of 1:0.5 was selected. Microvisualization experiments revealed that the modified nanoscale system achieves residual oil displacement through three mechanisms: emulsification (reducing residual oil droplet size to enhance mobility), wetting reversal (lowering contact angle to weaken adhesion), and structural separation pressure (counteracting capillary forces to destabilize residual oil). Displacement experiments reveal that in rock cores with permeability ranging from 1 to 100 mD, the modified system exhibits a recovery rate trend that initially increases and then decreases. Nevertheless, it consistently enhances recovery rates, maintaining them above 12%, demonstrating strong application potential.

Keywords: modified nano-SiO₂; interfacial tension; wettability; oil displacement; enhanced oil recovery



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1. Introduction

With the continuous growth of global crude oil demand, the efficient development of low-permeability reservoirs has become a core challenge urgently needing resolution in the oil and gas industry. Characterized by fine pore throats and poor flow capacity, such reservoirs exhibit extremely low recovery rates through traditional primary and secondary recovery methods, leaving substantial amounts of crude oil trapped underground [1], primarily due to the constraints of high IFT and capillary forces. Conventional enhanced oil

recovery (EOR) methods for low-permeability reservoirs include surfactant flooding and gas injection. While surfactant flooding offers certain advantages in improving displacement efficiency, it faces significant challenges in low-permeability reservoirs, including severe chemical adsorption losses and high costs [2,3]. Gas injection, on the other hand, is prone to gas channeling due to high flow resistance and significant fluid viscosity differences in low-permeability reservoirs, resulting in poor gas sweep efficiency [4,5]. To address these challenges, efforts are currently focused on the synergistic application of reservoir modification techniques (such as hydraulic fracturing [6]) and chemical enhanced oil recovery technologies, aiming to establish highly efficient flow pathways.

Nanomaterials have become a focal material in enhanced oil recovery research for low-permeability reservoirs due to their highly controllable surface properties. In recent years, the global oil and gas industry has achieved significant progress in nanomaterial applications, developing various nanoparticle materials including flake-shaped [7–9] and wire-shaped [10,11] nano-displacement agents. Among these, spherical nano-SiO₂ materials are particularly noteworthy for their low cost, environmental friendliness, and low flow resistance, enabling deeper penetration into reservoirs for more efficient physico-chemical interactions with rocks and crude oil, thereby improving displacement efficiency. However, single-component nano-SiO₂ particles exhibit strong hydrophilicity, poor dispersion stability in oil–water systems [12], and limited effectiveness in reducing oil–water IFT [13], making them inadequate for addressing the complex interfacial environment of low-permeability reservoirs. Recent studies indicate that modifying clay minerals with bio-surfactants can effectively enhance their dispersion and interfacial activity in oil phases [14]. This discovery offers new insights for the modification design of nano-enhanced oil recovery materials. By imparting amphiphilic properties to SiO₂ nanoparticles through surface modification techniques, these particles can efficiently adsorb at the oil–water interface within micro-pores of low-permeability reservoirs, significantly reducing interfacial tension [15,16]. Simultaneously, they regulate rock wettability [17,18] and improve displacement efficiency in complex flow channels, offering an innovative pathway to overcome technical bottlenecks in enhancing recovery rates from low-permeability reservoirs [19].

In recent years, significant progress has been made in the modification of nanomaterials. Cao's group [20] employed 3-aminopropyltriethoxysilane (APTES) and octyltriethoxysilane (OTES) to surface-modify nano-SiO₂, successfully introducing amino and alkyl groups to impart amphiphilic properties. This enables the formation of stable interfacial films at the oil–water interface. This material increased crude oil recovery by 10.3% in heterogeneous rock cores with permeability values of 50, 300, and 800 mD. Wu's team [9] prepared amphiphilic Janus nanosheets using graphene oxide and dodecylamine, featuring distinct hydrophilic and hydrophobic surfaces that effectively stabilize water-in-oil emulsions. Additionally, Li's team [21] developed novel amphiphilic carbon-nitrogen nanocrystal (ACN) nanofluids, achieving a 19.21% increase in recovery rate. These studies collectively demonstrate the immense potential of modified nanomaterials for enhancing oil recovery. However, existing work primarily focuses on verifying macro-scale oil displacement effects. While some studies have employed numerical models to analyze enhanced recovery mechanisms [22] and downhole flow behavior [23,24], research into key micro-scale mechanisms—such as how materials influence oil–water flow dynamics and drive oil droplet detachment—remains relatively scarce and warrants further exploration.

This study focuses on nano-SiO₂ as the research subject. Through the evaluation of temperature resistance, salt tolerance, and IFT reduction capability, an optimized compatible surfactant was selected to construct a SiO₂/CTAB system. The structural characteristics of SiO₂ powder before and after modification were characterized using XRD, FT-IR and transmission electron microscopy. IFT and contact angle measurements were conducted for systems with varying degrees of modification. Combined with visualization experimental techniques, the distribution of residual oil in reservoir pores and its interaction with oil/water phases were visually observed. Finally, the performance of this system was evaluated through oil displacement efficiency tests.

2. Materials and Methods

2.1. Materials

(1) Nano-SiO₂, self-developed in a laboratory [25] (particle size of 10 nm). (2) All surfactants used in this study were purchased from Shanghai Macklin Biochemical Co., Ltd. (Shanghai, China) Including Fatty alcohol polyglycol ether (AEO-9), Sorbitan monooleate (Span 80), Alkyl ether sulfate (AES), Polyethylene glycol monododecyl ether (Brij-35), Octylphenol-9 (Triton X-100), Octylphenol (Triton X-114), Polysorbate 80 (Tween 80), Nonylphenol ethoxylate (NP-40), Hexadecyl trimethyl ammonium bromide (CTAB), Sodium dodecyl sulfate (SDS), Sodium dodecyl benzene sulfonate (SDBS), and Octylphenol polyoxyethylene ether (OP-10). (3) Experimental oil samples: shale oil (viscosity 32.4 mP·s, density 0.813 g/cm³, from Bohai Oilfield), n-heptane (Shanghai Macklin Biochemical Co., Ltd.). (4) Staining materials: Sudan Red and Methyl Blue (Shanghai Macklin Biochemical Co., Ltd.). (5) Outcrop core (from Daqing Oilfield). Specific parameters are shown in Table 1.

Table 1. Core sample parameters.

No.	Gas Permeability (mD)	Length (cm)	Radius (cm)	Porosity (%)
1	1	10.452	1.256	9.89
2	50	10.621	1.261	13.24
3	100	10.231	1.259	17.43

2.2. Methods

2.2.1. Preparation of Modified Nanoparticles

A specific mass of nano-SiO₂ was dispersed in 100 mL of distilled water and subjected to ultrasonic treatment for 1 h to achieve uniform dispersion. An appropriate amount of surfactant was weighed and added to the nano-fluid at a certain concentration, followed by ultrasonic treatment at 60 °C for 1 h to obtain a uniformly dispersed modified nano-SiO₂ fluid. After freezing and drying, modified nano-SiO₂ solid particles were obtained.

2.2.2. Characterization Method

The particle size of silica was measured using a Nanoparticle Size Analyzer (Dieth-elm Keller Siber Hegner China Company, Shanghai, China). The micro-morphology of silica was analyzed using Transmission Electron Microscopy (Japan Electron Optics Laboratory Co., Ltd., Tokyo, Japan). The modified and unmodified silica particles were characterized using Fourier Transform Infrared Spectroscopy (Bruker Corporation, Billerica, MA, USA) and X-ray diffraction (Bruker Analytical X-Ray Solutions, Karlsruhe, Germany). The IFT between oil and water was measured using a Rotary Interfacial Tensiometer (Jinxiang Environmental Technology Company, Chengdu, Sichuan, China) with the pendant drop method. The contact angle was measured using a Contact Angle Goniometer (Sanchez Technologies, Viarmes, France) with the inverted method. The transmission light intensity

of the solution was measured using a Turbiscan Stability Analyzer (Microtrac Inc., Montgomery, PA, USA). The zeta potential of the nanofluid was measured using a Zeta Potential Analyzer (Malvern Instruments Limited, Great Malvern, UK).

2.2.3. Oil Displacement Experiment

Micro-scale oil displacement. First, the chip model is treated with a hydrophobic agent and left to stand for 1 h. The throat dimensions of the chip are 30–110 μm , as illustrated in Figure 1. For visualization purposes (to clearly observe the oil–water distribution and dynamic displacement process), oil-soluble dye materials are used to color n-heptane, while water-soluble dye materials are used to color deionized water. The dyed fluids are then filtered using a 0.2 μm filter for later use. The chip is first saturated with dyed oil and left to stand for one day. A water drive is then performed at a flow rate of 20 $\mu\text{L}/\text{min}$ until the outlet of the model produces liquid without oil; subsequently, a modified nano-SiO₂ system is injected at the same flow rate of 20 $\mu\text{L}/\text{min}$; followed by a secondary water drive at 20 $\mu\text{L}/\text{min}$.

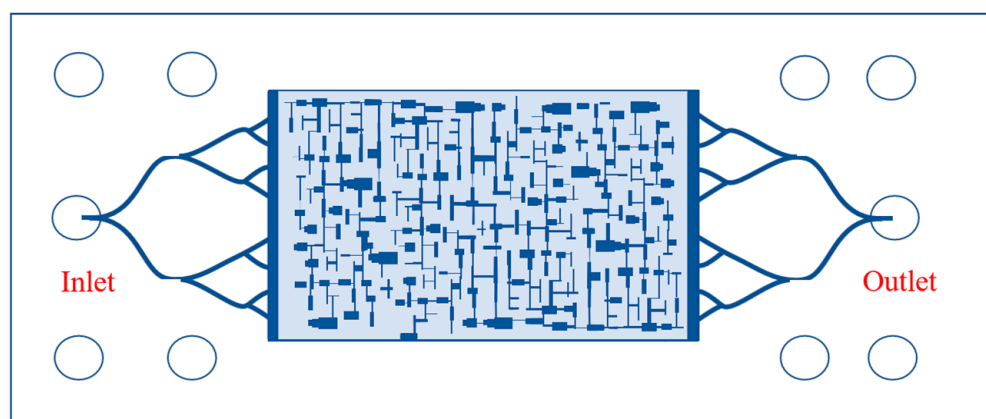


Figure 1. Chip model schematic.

Macro-scale oil displacement. After measuring the basic parameters of the core, the core is vacuum-saturated with water to calculate its pore volume; it is then saturated with oil and aged for 7 days to calculate the oil saturation; a water drive is conducted at a constant speed of 0.1 mL/min at 45 °C until the water cut reaches 98%. Inject 0.5 PV of modified nano-SiO₂ system. Conduct secondary water flooding until water cut reaches 98%, recording pressure in real time and calculating recovery rate. Data for each experimental group represents the average value obtained from three parallel experiments.

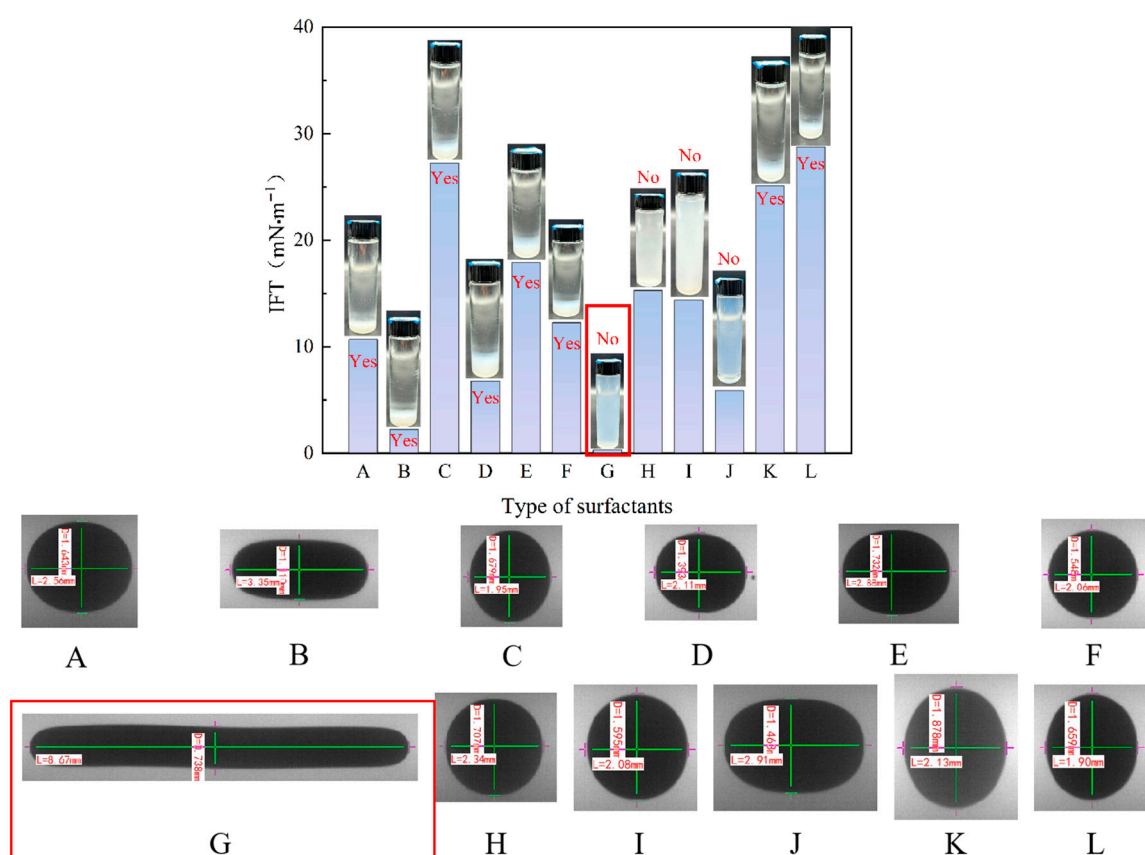
3. Results and Discussion

3.1. Preferred Surfactants

For 10 nm SiO₂ particles, the study selected 12 commonly used surfactants in oilfields for optimal blending with nano-SiO₂ materials. Using simulated water with a mineralization degree of 30,000 mg/L, the oil–water IFT of the system was tested after blending 0.1 wt% surfactant with 0.1 wt% nano-SiO₂. The mixture was then placed in an oven at 120 °C for 48 h to observe whether precipitation formed. Optimization was conducted using dispersion stability and interfacial tension as evaluation criteria, with results presented in Table 2 and Figure 2.

Table 2. Surfactant preferred.

Name	Code Name	IFT/(mN·m ⁻¹)	Precipitates
AEO-9	A	10.671	Yes
Triton X-114	B	2.241	Yes
Tween 80	C	27.240	Yes
Triton X-100	D	6.776	Yes
Span 80	E	17.893	Yes
Brij-35	F	12.255	Yes
CTAB	G	0.300	No
SDS	H	15.288	No
SDBS	I	14.376	No
OP-10	J	5.885	No
NP-40	K	25.119	Yes
AES	L	28.750	Yes

**Figure 2.** Surfactant preference results.

As shown in Table 2 and Figure 2, CTAB can reduce interfacial tension to the 10^{-1} mN/m level, demonstrating significant surfactant advantages. As a cationic surfactant, CTAB adsorbs effectively onto the surface of nano-SiO₂, where its dissociated cations bind to negatively charged silanol groups on the particle surface. This transforms the zeta potential from -25.37 mV before modification to $+42.31$ mV, achieving a complete reversal of surface charge. This change not only increases the positive charge density on the particle surface but also suppresses agglomeration by enhancing electrostatic repulsion between particles. Simultaneously, CTAB reduces the interfacial energy of the system and optimizes surface properties, maintaining excellent dispersion stability for nano-SiO₂. Therefore, CTAB is the preferred modifier for nano-SiO₂.

3.2. Characterization of Nano-SiO₂

In this study, 0.1 wt% SiO₂ solution and 0.1 wt% SiO₂ + 0.05 wt% CTAB solution were selected as the research subjects. The success of the modification of nano SiO₂ particles was evaluated through XRD, FTIR, transmission electron microscopy, and stability measurement experiments, and their micro-morphology and stability were characterized.

3.2.1. XRD

XRD analysis was conducted on two types of nano SiO₂ particles before and after CTAB modification to confirm the successful preparation of the modified nano SiO₂ particles. The results are shown in Figure 3.

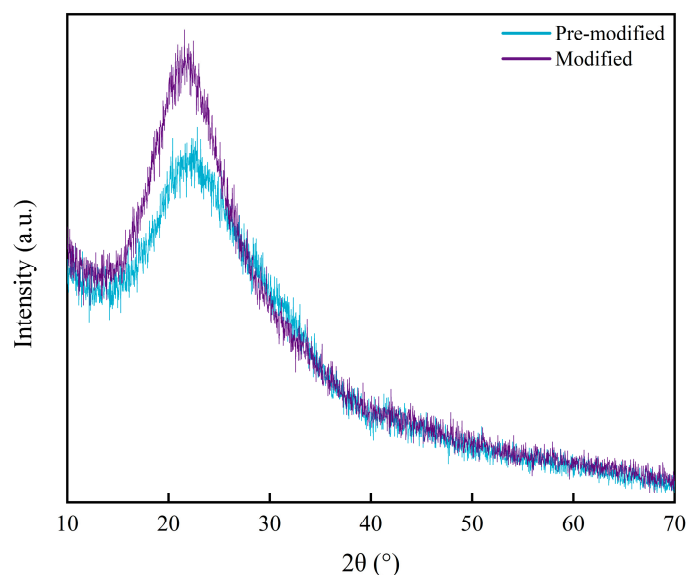


Figure 3. XRD spectra of nano-SiO₂ before and after modification.

As shown in Figure 3, the XRD patterns of the nano-SiO₂ particles before and after modification exhibit characteristics of amorphous SiO₂. A broad scattering peak is observed in the range of 2θ from 20° to 25° [26]. The intensity of the scattering peak region slightly increases after modification, and the peak shape also undergoes minor changes. These alterations indicate that CTAB interacts with the surface of SiO₂, affecting its short-range ordered structure, thereby confirming the successful modification of the nano-SiO₂ particles [27].

3.2.2. FT-IR

A functional group characteristic frequency distribution analysis was conducted on two types of nano-SiO₂ particles before and after CTAB modification, as shown in Figure 4.

The peak at 464.76 cm^{-1} corresponds to the bending vibration of Si-O-Si. The peak at 799.35 cm^{-1} represents the bending vibration of O-Si-O. The peak at 1101.15 cm^{-1} indicates the antisymmetric stretching vibration of Si-O-Si, with a stronger peak observed after modification, confirming the bonding of CTAB to the SiO₂ surface [28]. The peak at 951.70 cm^{-1} corresponds to the stretching vibration of Si-OH. The peak at 3438.46 cm^{-1} represents the antisymmetric stretching vibration of structural water -OH. The peak at 1631.48 cm^{-1} indicates the absorption of the bending vibration H-O-H in water molecules, suggesting that the coating of CTAB altered the surface properties of nano-SiO₂ and affected its water absorption capacity. The characteristic absorption peaks of the above nano-SiO₂ particles demonstrate the successful modification of SiO₂ by CTAB.

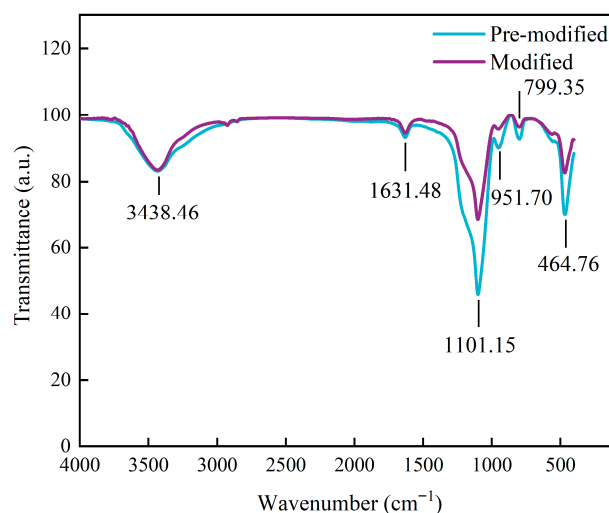


Figure 4. FTIR spectra of nano-SiO₂ before and after modification.

3.2.3. Particle Size and Shape

To investigate the changes in the physical properties of modified and unmodified nano-SiO₂ particles, comparative experiments were conducted using particle size analysis and transmission electron microscopy at the microscopic level. Figure 5a,b presents the particle size distribution and microscopic morphology of unmodified nano-SiO₂ particles. The analysis indicates that the unmodified nanoparticles are in an unstable thermodynamic state, influenced by interactions such as van der Waals forces and Coulombic forces, leading to agglomeration among the particles [29,30]. Figure 5c,d illustrates the particle size distribution and microscopic morphology of nano-SiO₂ particles after modification with CTAB. The results show that the dispersibility of nano-SiO₂ particles significantly improves after CTAB modification.

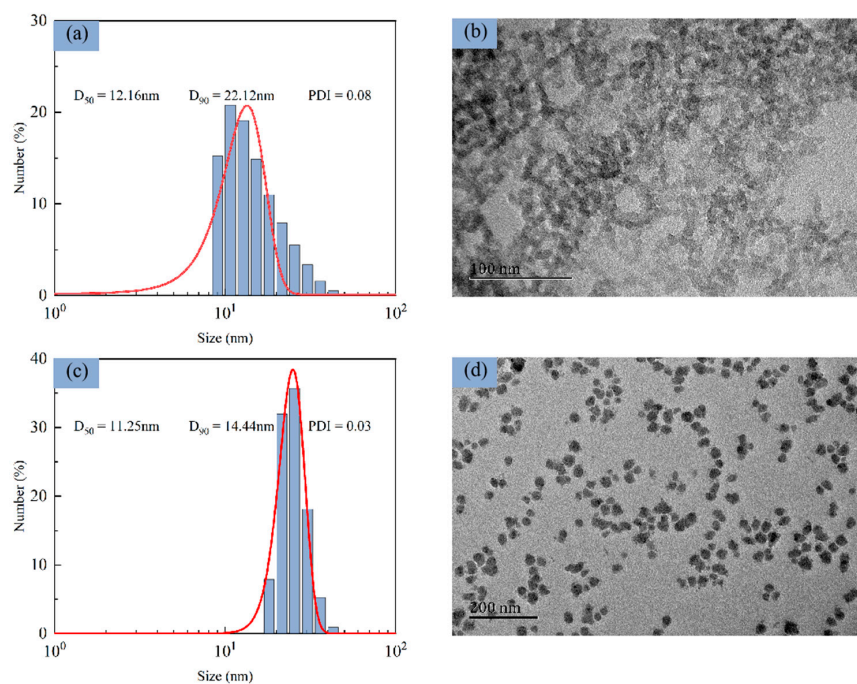


Figure 5. Particle size and morphology of nano-SiO₂ before and after modification. (a) nano-SiO₂ particle size before modification, (b) TEM of nano-SiO₂ before modification, (c) nano-SiO₂ particle size after modification, (d) TEM of nano-SiO₂ after modification.

3.2.4. Stability Analysis

This section focuses on the dispersion stability of modified and unmodified nano-SiO₂ fluids, with results illustrated in Figure 6. The intensity of transmitted light is negatively correlated with the volume concentration of nanoparticles [31]. According to the data presented, both modified and unmodified samples show an increasing trend in particle concentration around 0.5 mm, with the concentration increase in the unmodified samples being more pronounced. Furthermore, the transmitted light intensity of unmodified nano-SiO₂ is significantly higher than that of the modified samples. In contrast, the transmitted light intensity of the modified samples shows a more uniform distribution with changes in the height of the sample cell, indicating that the modified nano-fluid exhibits better stability. This phenomenon suggests that the modification of nano-SiO₂ with CTAB leads to the formation of an adsorption layer due to the introduction of quaternary ammonium groups on the surface, effectively suppressing particle aggregation caused by van der Waals forces, thereby enhancing the dispersion stability of the nano-fluid.

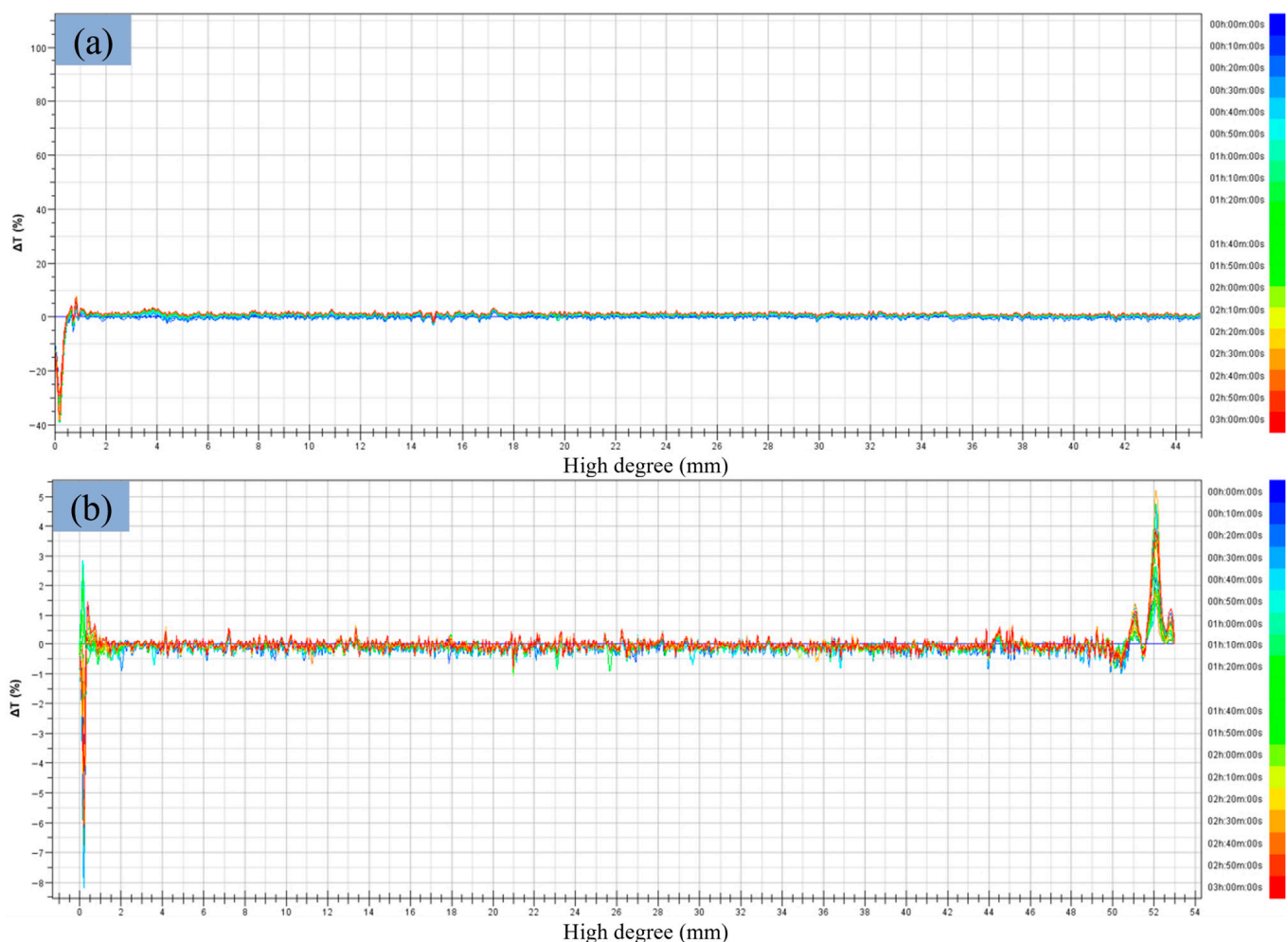


Figure 6. Transmission spectra of nano-SiO₂ before and after modification. (a) Before; (b) after.

3.3. IFT

Four different modified nano-SiO₂ solutions were prepared using deionized water, with ratios of 1:0.5, 1:1, 1:2, and 1:3. The specific formulations are as follows: (1) 0.1 wt% SiO₂ + 0.05 wt% CTAB; (2) 0.1 wt% SiO₂ + 0.1 wt% CTAB; (3) 0.1 wt% SiO₂ + 0.2 wt% CTAB; (4) 0.1 wt% SiO₂ + 0.3 wt% CTAB. The IFT of the four solutions was measured. As shown in Figure 7, the nano-SiO₂ solutions with different modification degrees effectively

reduced the IFT. With the increase in surfactant concentration, the oil–water IFT exhibited a trend of first decreasing and then slightly increasing: at low modification levels, CTAB molecules arranged orderly on the SiO_2 surface, enhancing the interfacial activity [32]. When the loading exceeded the critical value, the surface molecular chains became overly crowded, partially blocking the exposure of hydrophobic chains, leading to a slight increase in IFT. When the modification degree was 1:0.5, the oil–water IFT decreased to 0.221 mN/m, while at modification degrees of 1:1, 1:2, and 1:3, the oil–water IFT were 0.200 mN/m, 0.198 mN/m, and 0.202 mN/m, respectively. Considering the economic benefits, subsequent studies will select the nano- SiO_2 solution with a modification degree of 1:0.5.

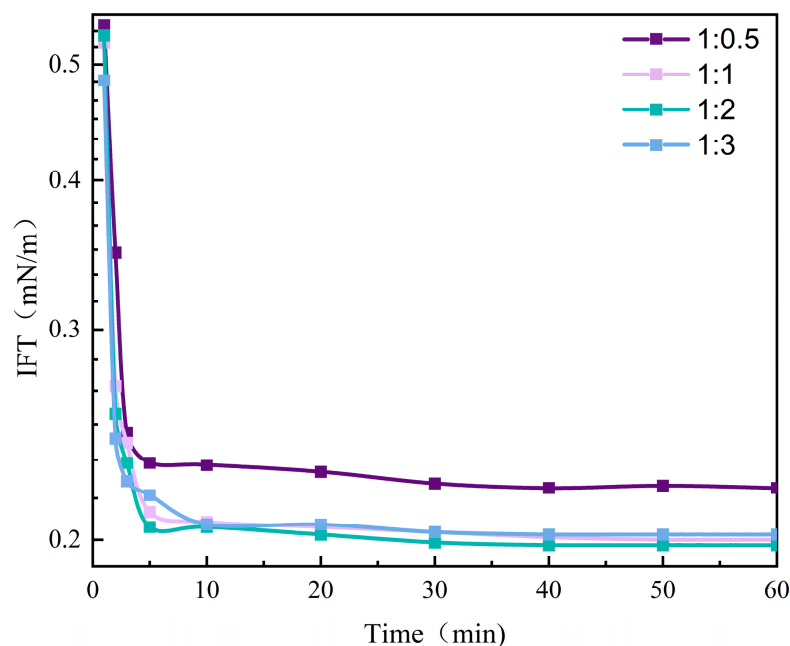


Figure 7. Effect of different degrees of modification on IFT.

3.4. Wettability

An aqe solution prepared by mixing concentrated sulfuric acid and 30% hydrogen peroxide in a 7:3 volume ratio was used to remove impurities and organic matter from quartz plates. The plates were rinsed with deionized water until clean, washed twice with anhydrous ethanol, air-dried, and then immersed in a 5 wt% trimethylchlorosilane methanol dispersion for 48 h. The treated oleophobic quartz wafers were inverted onto quartz trays containing nano- SiO_2 solutions with varying modification ratios (1:0.5, 1:1, 1:2, 1:3). The oil–water contact angles on the quartz surfaces were measured using a contact angle measuring instrument.

As shown in Figure 8, the oil–water contact angle in deionized water was 105.67° , while the equilibrium oil–water contact angles for the four silica nano-solutions with different modification ratios were 28.68° , 27.02° , 30.34° , and 40.29° , respectively. These results indicate that all four modified silica solutions effectively alter wettability, transforming quartz substrates from oil-wetted to strongly water-wetted surfaces, thereby enhancing crude oil displacement efficiency [18].

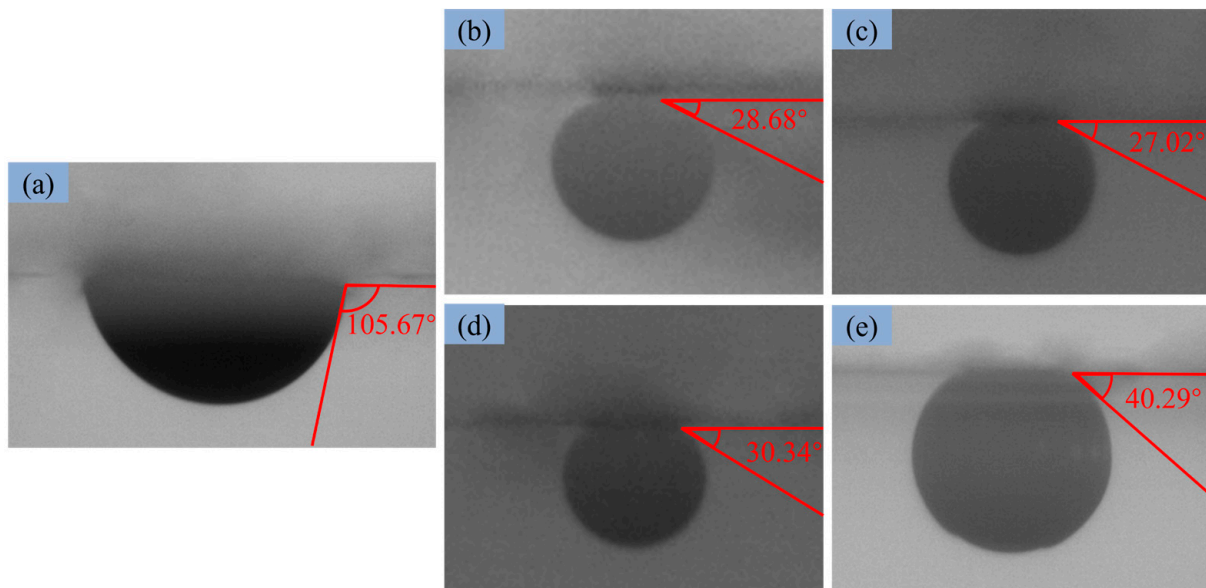


Figure 8. Effect of different degrees of modification on wettability. (a) Water, (b) 1:0.5, (c) 1:1, (d) 1:2, (e) 1:3.

3.5. Mechanism of Oil Displacement

Based on the aforementioned experimental evaluation and economic benefit analysis, we select a modified nano-SiO₂ system with a nanoparticle concentration of 0.1 wt% and a CTAB concentration of 0.05 wt% for micro-oil displacement experiments. By observing the flow characteristics of the nanofluid in the chip, we delve into the mechanism of mobilizing the residual oil at the micro level. Figure 9 illustrates the oil–water distribution under saturated oil conditions, primary water flooding conditions, and secondary water flooding conditions. The observations indicate that after primary water flooding, a significant amount of residual oil remains in the pore structure, particularly in the corners of the pores, throat regions, and on the rock surface. Following the displacement with the nanofluid, the distribution of residual oil changed significantly; the residual oil that was originally trapped in the channels was removed, indicating that the injection of the nanofluid reduced the oil–water viscosity and expanded the swept volume [33–35]. Through binarization processing for quantitative analysis of the residual oil, the oil saturation after primary water flooding was calculated to be 52.70%, while the oil saturation after secondary water flooding was 38.42%, indicating that this system can significantly enhance the displacement efficiency of residual oil after water flooding.



Figure 9. Visualization of oil–water distribution during micro-scale oil displacement (red represents oil and blue represents water). (a) Saturated oil, (b) primary water flooding, (c) secondary water flooding.

Microscopic images reveal the presence of numerous irregularly shaped residual oil droplets and oil films within the pores of the reservoir after water flooding. These residual oils primarily adhere to the pore walls and throat regions. By capturing images during the microscopic displacement process, the study found that a relatively stable emulsion system was formed after the injection of the nanofluid. This system reduces the tendency for oil droplets to coalesce, and the reduction in droplet size facilitates their transport [36] (as shown in Figure 10a). Furthermore, the wettability reversal capability of the nanofluid alters the surface properties of the rock, gradually transforming the originally oleophilic surface into a hydrophilic state. This change disrupts the adhesion balance between the oil droplets and the rock, promoting the detachment of oil droplets from the pore walls into the flowing phase [37] (as illustrated in Figure 10b). Additionally, the thick oil film formed after nanofluid driving is unstable and creates oil rings, which, under the influence of structural separation pressure, leads to the formation of spherical oil droplets from the oil rings on the solid surface, thereby stripping the remaining oil from the rock surface [38] (as depicted in Figure 10c). The above results indicate that the nanofluid system primarily facilitates the removal of residual oil droplets and oil films left in the channels after water flooding through emulsification [39,40], wettability reversal [41,42], and structural separation pressure [43,44]. This process effectively clears the residual oil blockage in the channels, achieving an enhancement in oil recovery.

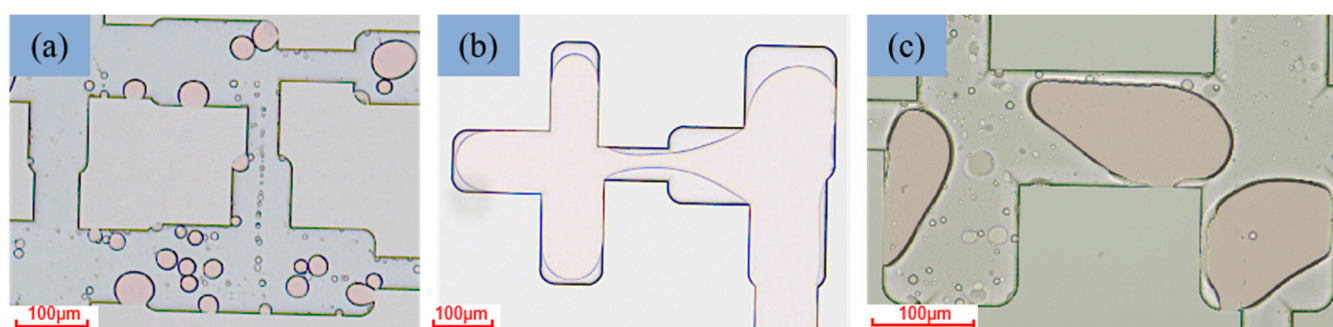


Figure 10. Micro-scale oil displacement process diagram (red represents oil and blue represents water). (a) Emulsification, (b) wettability reversal, (c) structural separation pressure.

3.6. Evaluation of Oil Displacement Effect

At a temperature of 45 °C, oil displacement experiments were conducted for this system within the target reservoir permeability range. The displacement efficiency at different permeabilities is shown in Figure 11 and Table 3. For a core with a permeability of 1 mD, the recovery rate during the primary water flooding stage was 24.72%. Following injection of 0.5 PV of the modified nano-SiO₂ system, subsequent water flooding reduced water cut by up to approximately 15%, increased recovery by 12.51%, and achieved a final recovery rate of 37.23%. This demonstrates that the modified nano-SiO₂ system exhibits favorable water reduction and oil enhancement effects under this permeability condition. The recovery increment for the 50 mD medium-permeability core reached 17.37% (peak), attributed to the optimal matching between pore throat dimensions and nanoparticle size, achieving synergistic optimization through uniform adsorption, efficient oil displacement, and full-pore-scale propagation. The recovery increment for 100 mD high-permeability cores was 16.56%, slightly lower than at 50 mD. This was primarily due to the development of dominant flow channels under high-permeability conditions, causing preferential flow through these channels. Consequently, residual oil in non-dominant channels was not fully displaced, resulting in a slight decline in sweep efficiency. In summary, the system demonstrates optimal oil recovery increment at 50 mD due to the absence of significant channeling effects and optimal throat-pore matching.

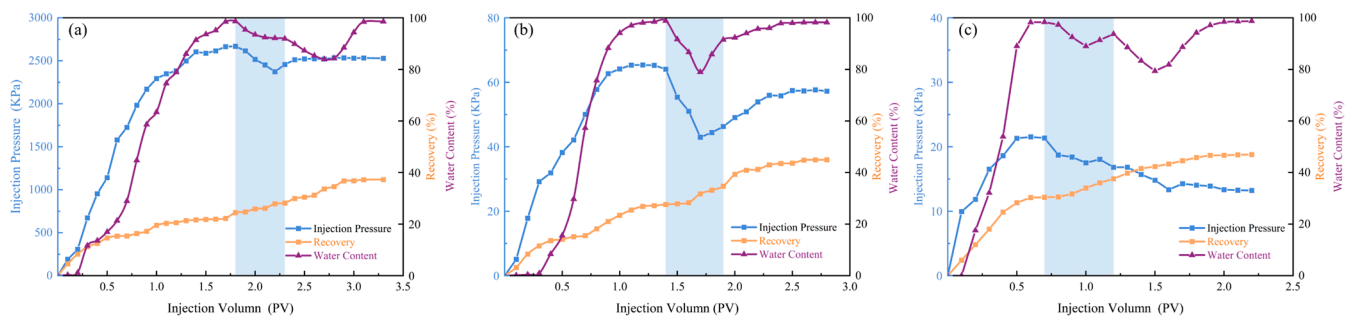


Figure 11. Oil displacement effect of modified nanofluid at different permeabilities: (a) 1 mD, (b) 50 mD, (c) 100 mD.

Table 3. Effect of modified silica nanofluid for enhanced recovery at different permeabilities.

No.	Gas Permeability (mD)	Primary Water Flooding Recovery (%)	Final Oil Recovery (%)	Enhanced Oil Recovery (%)
1	1	24.72	37.23	12.51
2	50	27.58	44.95	17.37
3	100	30.40	46.96	16.56

4. Conclusions

The CTAB-modified nano-SiO₂ system exhibits excellent dispersion stability at high temperatures. CTAB effectively shields the van der Waals forces between SiO₂ particles, inhibiting particle agglomeration. XRD and FT-IR analyses confirm the successful modification of SiO₂ particles. The CTAB-modified nano-SiO₂ fluid demonstrates outstanding interfacial activity, significantly reducing the oil–water IFT to the magnitude of 10^{−1} mN/m. As the degree of modification increases, the oil–water IFT initially decreases and then slightly increases. Furthermore, the modified nano-SiO₂ fluid alters the surface properties of rocks through an “adsorption-wettability reversal” mechanism. The adsorption of nanoparticles onto the rock surface introduces a large number of hydrophilic groups, transforming the originally oil-wet rock surface into a strongly hydrophilic one, with the contact angle drastically reduced to 30°. This transformation provides a crucial basis for enhancing crude oil displacement and improving reservoir development efficiency through interfacial and wettability regulation. Considering economic factors, a modified nano-SiO₂ system composed of 0.1 wt% SiO₂ and 0.05 wt% CTAB is selected for micro and macro-scale oil displacement experiments. The micro-scale oil displacement studies indicate that this modified nano oil displacement system can effectively carry out residual oil trapped in the channels through emulsification, wettability reversal, and structural separation pressure. The results of the oil displacement experiments show that when this system is applied to cores with permeabilities of 50–100 mD, it can increase the recovery rate by more than 15% (Table 3), demonstrating significant effectiveness and good potential for field application.

Author Contributions: Conceptualization, T.C.; Investigation, T.C., H.L., J.D., Y.R. and X.G.; Data curation, Y.R.; Supervision, J.W., J.D., H.L. and X.G.; Writing—original draft, T.C.; Writing—review and editing, J.W. and H.L. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: Author Huaizhu Liu was employed by the Tangshan Jiyou Ruifeng Chemical Limited Company, Petro China Company Limited. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be considered as a potential conflict of interest.

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