

Article

The Evolution Law of Wettability Degree After Energy Replenishment in Tight Type-II Reservoirs with Different Pore Structures

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Abstract

Tight oil is an important resource replacement in the petroleum industry, with the reserves of Type-II energy accounting for over 40%. However, these reservoirs have small pore throats and complex structures, and their wettability directly affects the EOR by affecting the occurrence of crude oil and multiphase flow mechanisms. In response to an unclear understanding of the evolution mechanism of wettability after energy replenishment in tight reservoirs with different reservoir formation conditions, the evolution law of wettability in different energy replenishment media for tight type-II reservoirs is evaluated by performing wettability experiments and nuclear magnetic resonance experiments, and the mechanism of differential changes in wettability after energy replenishment in different media is elucidated. The results show that the block with well-developed pores and good connectivity (Block: Z401) had the smallest in situ wetting angle, ranging from 27.1° to 30.4° , and that the interface effect had a small impact, resulting in a small change in the wetting angle after energy replenishment. The wetting angle of the developmental intersection block (Block: G93) is the highest, ranging from 36.6° to 46.4° . The connected pore and throats fully interact with the medium at the interface, resulting in a significant change in the wetting angle. In addition, after natural gas energy supplementation, the principle of similar solubility causes a significant change in the wetting angle of the pore throat interface after adsorption, with a maximum angle of 19.6° . The change in the wetting angle change of the CO_2 mixed-phase principle is in the middle, at about 13.6° , while the change in the wetting angle is minimal after N_2 replenishment, around 10° . The research results improve our understanding of the basic theory of tight oil supplementary energy development and have important practical significance.

Keywords: tight reservoir; wettability; CO_2 EOR

Academic Editors: Zhenlong Song and Kunpeng Zhang

Received: 3 June 2025

Revised: 19 June 2025

Accepted: 25 June 2025

Published: 1 September 2025

Citation: Li, C.; Yin, D. The Evolution Law of Wettability Degree After Energy Replenishment in Tight Type-II Reservoirs with Different Pore Structures. *Processes* **2025**, *13*, 2797. <https://doi.org/10.3390/pr13092797>

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1. Introduction

Tight oil usually refers to reservoirs with a permeability of less than $0.1 \times 10^{-3} \mu\text{m}^2$. The importance of wettability in tight reservoirs mainly lies in its direct impact on the occurrence, flow patterns, and development effects of oil and gas. Firstly, it controls the formation and occurrence of oil reservoirs; second, wettability determines the efficiency of oil displacement through infiltration and absorption, directly affecting the EOR.

Generally speaking, the smaller the wetting angle, the stronger the hydrophilicity, and the capillary force of two-phase flow acts as a resistance to affect oil production. Elucidating the impact mechanism of different energy replenishment media on reservoir wettability

is helpful for the efficient development of tight oil. In the past decade, research on the wettability of tight oil has mainly focused on the impact of wettability on the definition, measurement methods and influencing factors of tight oil extraction. Austad et al., Iglaier et al., and Armstrong et al. extensively studied the wetting behavior and scale of rocks in the context of improving oil recovery (EOR) and CO₂ geological storage [1–3]. To evaluate the wettability of the surface, different methods can be used, including contact angle measurement [4], molecular dynamics prediction [5,6], the Amott test, the Amott–Harvey index, and USBM (using the ratio of positive and negative work in capillary pressure curves to quickly determine the wetting preference). The measurement of the contact angle is considered a reliable method for wetting characterization [7,8], which can directly measure surface wettability and has wide applicability in evaluating the wettability of conventional reservoirs, but may produce results that are different from those of shale reservoirs [9]. Siddiqui et al. found that water does not contain surfactants based on contact angle measurements [10]. Rücker et al. proposed a wettability upscaling method based on it, which considers the changes in wettability from the nanoscale to the core scale [11]. Due to issues such as surface contamination, uneven surface roughness, and compositional heterogeneity, the contact angle method has rarely been used to evaluate shale wettability. Spontaneous water absorption (SI) has been considered as an alternative method for evaluating shale wettability. Spontaneous imbibition is a phenomenon in which porous medium rocks spontaneously absorb wetting liquids under the action of capillary forces when in contact with them. In its initial stage, the capillary pressure is at its maximum, and the wetting phase fluid is rapidly absorbed into the pore network. As the intake of wetting phase fluid increases, the capillary force gradually decreases [12–16]. Wang et al. conducted nuclear magnetic resonance (NMR) imaging to measure the wettability of porous rocks [17]. Wang and Xin et al. used NMR combined with contact angle measurements and found that the wettability of the shale interior and surfaces gradually changes from water wetting to oil wetting when vitrinite reflectivity (R_o) > ~1.20% and that the degree of oil wetting continues to increase as maturity increases [18]. Rosneft compared the results of NMR relaxation measurements with data obtained from the direct measurement of wetting edge angles and indirect centrifugation using the Tulbovich method, demonstrating good qualitative and quantitative convergence between NMR relaxation measurements and direct studies of contact angles [19]. Amott and USBM testing are the most used methods for quantifying reservoir wettability, but USBM methods cannot strongly identify water or oil wet systems, while Amott methods cannot distinguish the importance of strong water and oil wet systems. Sheshdeh used the Amott USBM method [20] and considered saturation changes under zero capillary pressure to make the results more accurate. On this basis, Ghedan adopted the RIC method [21] to measure the wettability of the contact angle relatively quickly and accurately without using complex equipment. The microscopic oil recovery efficiency is greatly influenced by capillary forces, which depend on the type of rock wettability and can be explained by the critical separation pressure, which largely determines the success or failure of the oil recovery process [22–24]. The theories that explain the mechanisms behind changes in rock wettability include electrostatic interactions, surface adsorption, acid–base interactions, and ionic bonds [25], so many scholars use surfactants to alter rock wettability. Pinto et al. successfully enhanced the hydrophilicity of carbonate rocks and improved recovery rates without significantly reducing IFT [26]. Compared with traditional saltwater, smart water counteracts preferential water flow through cracks by optimizing the ion composition of water, thereby changing its wettability, making the oil phase more fluid, enhancing its distribution within the reservoir, and promoting deeper penetration into the rock matrix [27]. Optimizing salinity can lead to the required changes in wettability [28], and reducing the salinity of injected water decreases

the wettability of oil [29]. Mahani et al. and Chen et al. evaluated the effect of sulfate ions and determined that sulfate ions have a significant impact on reducing the wettability of oil. Intelligent water flooding has established screening criteria for the optimal salinity and ion range [30]. Iglauder et al. and Hashemi et al. demonstrated that sandstone exhibits a transition from strong to moderate moisture during hydrogen storage, while sulfate-reducing bacteria can cause a significant increase in contact angle measurements, resulting in a shift in wettability from water wet to moderate wet [31–35]. 3-Pentone has been identified as a promising wetting modifier for EOR in tight reservoirs, and its ions can alter surface wetting behavior, providing a simple, environmentally friendly, and cost-effective EOR method in low-permeability formations [36–38]. In addition, Zeta potential is another important indicator of wettability. By determining the charge at the solid–liquid interface of the shear plane, we can gain a deeper understanding of the stability of surfactants. Several studies have investigated the Zeta potential of shale treated with surfactants and found that wettability is related to surface chemical functional groups [39–45]. In addition to the above methods, many scholars also use combination methods. Alzaabi used contact angle measurements and Zeta potential analysis to investigate the effect of wettability changes [46]. Gao et al. qualitatively studied the wettability of shale samples through contact angle measurements and a comparison of directional self-priming behavior, as well as nuclear magnetic resonance methods [13]. Zhang et al. used spontaneous water absorption and nuclear magnetic resonance experiments to study the wettability characteristics of shale before and after extraction, and found that macropores have a significant impact on water wettability, while micropores and mesopores have a significant impact on oil wettability [47]. The advantages and disadvantages of existing wetting research methods are analyzed, which are reflected in Table 1.

Table 1. Research methods and applicability of wettability by different researchers.

Researchers	Research object	Methods	Advantage	Disadvantage
Gao, Zhiye, et al. [9]	Shale	CA	Intuitive and simple	Destructive experiment, slicing requires smoothness
Iglauder [5]	Quartz	MS	Accurate simulation	Unclassified non-uniformity
Ghedan [21]	Carbonate rocks	RIC	Simulate the process of reservoir formation	Poor quantitation
Pinto [26]	Carbonate rocks	Surfactant	Dynamic test	Destructive experiment, slicing requires smoothness
Sheshdeh [20]	-	Amott-USBM	High precision	Long testing time and large model error
Zhang, Weihang, et al. [47]	ZLJformation Dongyueyu section shale	SI, NMR	Consider the fluid characteristics	Complex data processing with model errors
Alzaabi [46]	Shale	Zeta potential	Strong continuity	Multiple solutions

The existing research often focuses on the static characteristics of undeveloped oil reservoirs, especially in the initial stage through the core testing of static wetting angles, ignoring the differences between different rock types and the potential changes in wettability after injecting a supplementary medium. Therefore, this paper conducts research on the evolution law of the wettability of tight oil reservoirs with different rock types after injecting an energy supplement medium. The research sequence is as follows: firstly, we quantitatively characterize the pore structure characteristics of different rock types through CT scanning and mercury intrusion experiments, and analyze the differences. We then conduct experiments on the flowability of different energy replenishment media to evaluate the changes in wettability after energy replenishment. Finally, based on the

nuclear magnetic resonance relaxation time spectrum, we elucidate the differential reasons for the changes in wettability. The research results of the paper improve the basic theory of tight oil reservoir development.

2. Differences in Wettability Evolution Characteristics

Wettability is usually characterized by the contact angle. To analyze the changes in core wettability caused by different energy replenishment media and their effects on permeability and absorption, this paper evaluates the characteristics of wettability changes before and after energy replenishment based on comprehensive industry-standard reservoir wettability experiments, and quantifies the changes in wettability angle.

2.1. Experimental Materials

By using laboratory dynamic and static contact angle measuring instruments to measure the contact angle, and comparing the changes in contact angle before and after saturation with different pressurized energy supplement media, the influence of different pressurized energy supplement media on the comprehensive wettability of the reservoir is analyzed. Simultaneously, utilizing the fact that the self-priming capacity of the rock water phase in wet reservoirs is greater than that of the oil phase, the spontaneous imbibition of rocks in the oil phase is greater than that in the water phase in lipophilicity reservoirs. We analyzed the changes in the imbibition of rock cores in saline and kerosene, and compared the effects of saturated different pressurized energy supplement media on imbibition before and after saturation. Finally, we used nuclear magnetic resonance technology to describe the wetting situation in micropores and determine the overall wettability of the rock and different sizes of pore throats based on imbibition curves and nuclear magnetic resonance T2 spectra.

The experiment selected natural rock cores with the same or similar permeability and porosity in each block, and sliced them according to the requirements of the industry standard “SY/T 5153-2017—Determination Method for Wettability of Reservoir Rocks” [48], with a specification of 25 mm × 2 mm, as shown in Figure 1.

2.2. Wettability Experiment

2.2.1. Experimental Methods

Based on the wettability experiments, the changes in the wetting angle of different types of Type-II tight reservoirs after saturation with different energy replenishment media are evaluated. The experimental procedure is as follows:

- (1) Core slice. The size is 25 mm × 50 mm;
- (2) Sample drying. Place the sliced rock cores into a constant-temperature oven (80 °C) for 12 h to dry;
- (3) Liquid squeezing. Place the core slice on the operating table and squeeze 10 µL of liquid;
- (4) Measure the wetting angle and take photos. Rotate the worktable lifting handwheel to make the surface of the sample contact the droplet and ensure that the droplet is displayed in the window. The software will automatically capture images according to the set data until completion.
- (5) After saturating the rock sample with CO₂ and N₂, repeat steps (1) to (4) to evaluate the changes in the wetting angle after different media are energized.

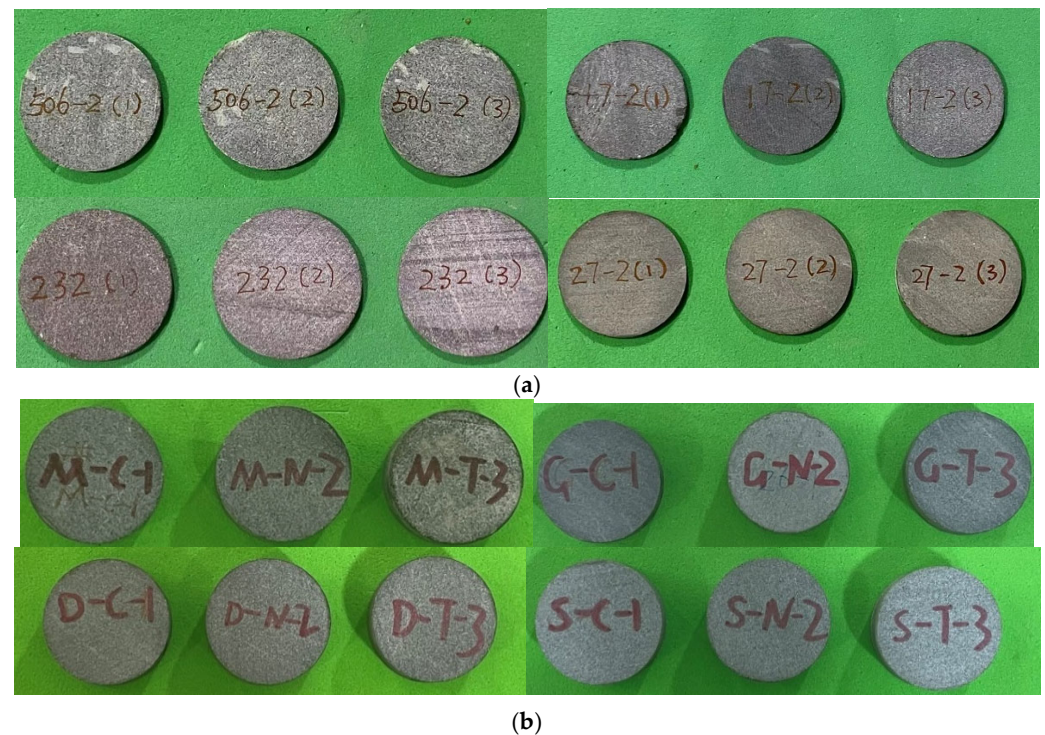


Figure 1. Experimental core material. (a) Comprehensive wettability evaluation of reservoir rock samples; (b) Spontaneous imbibition experiment core.

2.2.2. Results and Discussion

The wetting angle test results before and after energy replenishment for typical blocks of tight Type-II reservoirs are provided. Two experiments for each scheme were conducted in this study, and the average value was used as the wetting angle test result to provide an experimental basis for subsequent evaluation. The results are shown in Table 2.

From the experimental results before the saturation of the medium, the average contact angle range of the cores wettability tests was 27~40.4°. According to the wettability judgment criteria, this clearly indicates that the cores have the characteristic of hydrophilicity and belong to the strong hydrophilicity category. At the same time, the average contact angle of the rock samples in Block G93 is the smallest, at 27°. Due to its poor pore development and the reservoir characteristics, it exhibits the strongest hydrophilicity in terms of wettability. Relatively speaking, the average contact angles of the rock samples in the other three blocks are basically similar, at 38.2°, 37.6°, and 40.4°, respectively, with similar hydrophilicity and no significant difference.

Table 2. Contact angle results before and after saturation of different media in each block.

Block	Core No.	Before Replenishing Energy			Medium	After Replenishing Energy			Wettability	Permeability (mD)	Porosity (%)
		Contact Angle (°)	Avg (°)	Visualization		Contact Angle (°)	Avg (°)	Visualization			
M2	506-2-1	41.20	42.46		CO ₂	52.16	53.93		hydrophilic	0.0284	8.79
		44.08				55.70					
	506-2-2	31.54	36.35		N ₂	35.49	47.40		hydrophilic		
		41.16				59.31					
	506-2-3	48.78	47.29		Natural gas	62.59	66.47		Hydrophilic (weak)		
		45.79				70.35					
Z401	17-2-1	23.97	27.05		CO ₂	38.42	37.33		hydrophilic	0.0649	8.35
		30.13				36.24					
	17-2-2	23.79	37.12		N ₂	43.58	36.94		hydrophilic		
		50.45				30.30					
	17-2-3	27.20	30.37		Natural gas	28.14	24.87		hydrophilic		
		33.54				21.60					
S123	232-1	49.94	61.38		CO ₂	63.74	66.30		Hydrophilic (weak)	0.0405	10.55
		72.81				68.85					
	232-2	36.29	34.81		N ₂	49.04	39.63		hydrophilic		
		33.32				30.21					
	232-3	39.46	35.78		Natural gas	54.94	42.88		hydrophilic		
		32.10				30.82					
G93	27-2-1	43.90	46.39		CO ₂	29.52	37.77		hydrophilic	0.0264	10.36
		48.87				46.02					
	27-2-2	33.68	42.59		N ₂	43.58	33.79		hydrophilic		
		51.49				23.99					
	27-2-3	35.44	36.62		Natural gas	53.88	51.92		hydrophilic		
		37.79				49.96					

From the analysis of the contact angle results before and after saturation with different media in each block, it can be concluded that all the wettability is hydrophilic. However, due to the differences in pore throat structures in each block, the change in contact angle after injecting the energy replenishment medium causes changes in the hydrophilicity of some blocks. The maximum change in contact angle before and after the saturation of natural gas in the M2 block rock sample is observed, with an average increase of 19.18° from 47.29° to 66.47° . Due to the well-developed micro pore system and better pore sorting, the wettability of the rock sample changes from strong hydrophilicity to weak hydrophilicity. The change in the contact angle of the rock sample in Block Z401 before and after saturation with CO_2 is the largest, with an average increase of 10.28° from 27.05° to 37.33° . The pore and throat volumes are the largest, and the wettability of the block before and after saturation with the three media still belongs to strong hydrophilicity, with no significant change in wettability. The S123 block is mainly characterized by the development of small and medium-sized pores, with poor pore connectivity but good throat connectivity. The contact angle changes before and after saturation with three different media are relatively small. The average contact angle before and after saturation with CO_2 and N_2 increased by 4.92° and 4.82° , respectively, while the average contact angle before and after saturation with natural gas increased by 7.10° . The overall wettability shows non-significant changes. The contact angle of the rock samples in Block G93 changes significantly before and after saturation with N_2 and natural gas. The average contact angle before and after saturation with N_2 decreased by 8.80° , while the average contact angle before and after saturation with natural gas increased by 15.30° . The average contact angle before and after saturation with CO_2 changes relatively little, with an average decrease of 8.62° . Due to the development of small and medium-sized pores, the average throat length and volume are the smallest, and the connectivity between pores is poor, the wettability of the block before and after saturation with the three media still belong to strong hydrophilicity, and there is no significant change in wettability.

2.3. Nuclear Magnetic Resonance Analysis

The difference in wettability between different energy replenishment media is caused by fluid solid reactions, the fluid distribution, and coverage range, mainly in the affected areas of different media. Therefore, this study conducted nuclear magnetic resonance experiments before and after energy replenishment to clarify the mechanism of wettability changes.

The results of the spontaneous imbibition and T2 peak area growth rate of rock cores before and after energy supplementation in different blocks are presented in Table 3, and the reasons for the differences in wettability are analyzed.

Based on a comparison and analysis of the infiltration and absorption results of different saturated media and the changes in the T2 spectral peak area in the four blocks mentioned above, it can be concluded that after injecting CO_2 as a supplementary medium into the core of Block M2, the increase in saturated formation water is 6.02%, and the changes in wettability are mainly due to medium to large pores. After injecting natural gas as a supplementary energy medium, the increase in saturated formation water is 21.44%, and the change in wettability is mainly due to large, medium, and small pores. Injecting different energy supplement media into the core of Block Z401, the change in wettability is mainly due to macropores, while CO_2 causes a more significant change in the wettability of mesopores corresponding to the peak. The injection of different energy replenishment media into the core of block S123 resulted in changes in wettability mainly due to macropores, with CO_2 and natural gas causing a decrease in macropore hydrophilicity. The injection of CO_2 energy supplement media into the core of the G93 block results in the largest increase in the wettability of small and medium-sized pore water corresponding to the peak value, followed by natural gas.

Table 3. T2 peak area growth rate of different saturated media infiltration results in each block.

Block	Core No.	Dry Weight/g	Wet Weight/g	Water Absorption/g	Dry Weight/g	Medium	Wet Weight After Supplement/g	Water Absorption/g	Peak Area of T2 Spectrum Before Saturation Medium	Peak Area of T2 Spectrum After Saturation Medium	Peak Area Growth Rate/%
M2	M-C-1	11.760	11.848	0.088	11.769	CO ₂	11.841	0.072	7841.03	8312.86	6.02
	M-N-2	11.631	11.716	0.085	11.641	N ₂	11.711	0.070	8246.82	8148.99	−1.19
	M-T-3	11.790	11.879	0.089	11.797	natural gas	11.896	0.099	7565.23	9187.13	21.43
Z401	D-C-1	11.705	11.824	0.119	11.641	CO ₂	11.809	0.168	6071.16	5679.95	−6.44
	D-N-2	11.618	11.736	0.118	11.544	N ₂	11.752	0.208	6473.21	7028.68	8.58
	D-T-3	11.173	11.305	0.132	11.112	natural gas	11.317	0.205	6732.28	6719.89	−0.18
S123	S-C-1	11.526	11.699	0.173	11.529	CO ₂	11.741	0.212	6898.80	7871.60	14.10
	S-N-2	11.525	11.706	0.181	11.510	N ₂	11.754	0.244	7034.26	8579.45	21.96
	S-T-3	11.645	11.853	0.208	11.626	natural gas	11.896	0.270	886.03	8853.47	12.26
G93	G-C-1	11.885	11.995	0.110	12.003	CO ₂	12.033	0.030	5544.42	7329.38	32.19
	G-N-2	12.149	12.319	0.170	12.160	N ₂	12.317	0.157	8992.97	8843.20	−1.66
	G-T-3	11.327	11.438	0.111	11.280	natural gas	11.467	0.187	6159.28	7090.08	15.11

Taking the M2 block and G93 block as examples, the water absorption nuclear magnetic resonance results before and after soaking in different media are plotted. The results show that overall, there was a small change in the pore water absorption before and after the saturation of the medium in the four blocks with around 140, but that it did not fundamentally change the water wet properties of the pores. The micropores in the four blocks still have water wet properties, indicating that the three types of pressurized energy supplement media will not change the wettability of the micropores in tight oil, as shown in Figure 2.

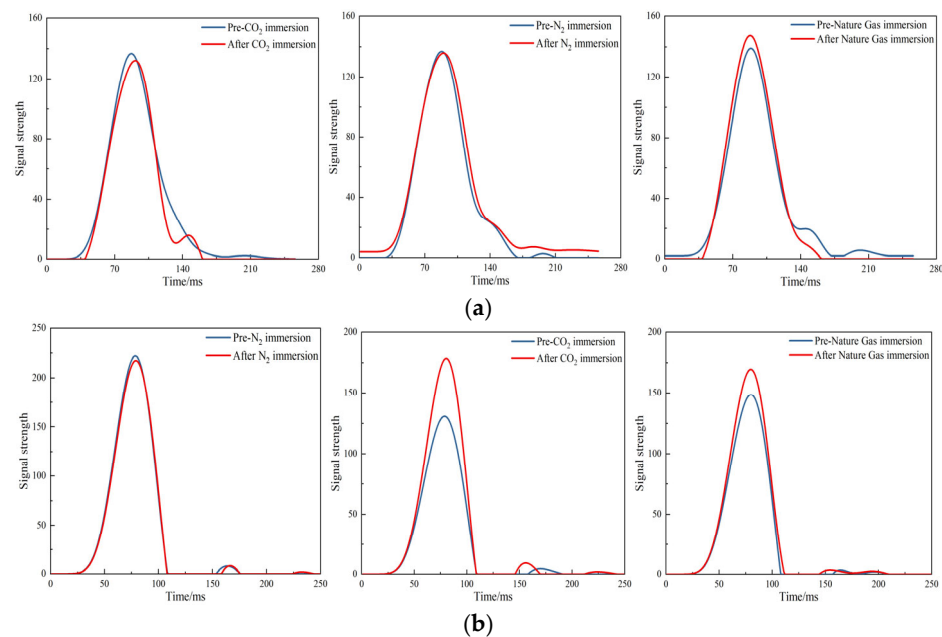


Figure 2. Comparisons of NMR spectra before and after energy supplementation with natural gas, CO₂ and N₂ in M2 block (a) and G93 block (b).

3. Analysis of Factors Influencing Wettability Evolution

The experimental results and an in-depth analysis of the differences between pore throat structures and the reasons for the differences in the evolution of wettability degree after energy replenishment medium are provided.

3.1. Pore Throat Structure

The changes in the wetting angle before and after energy supplementation with different media in each block are compared, as shown in Figure 3. The results indicate that when considering the injection of the same medium with different rock types, the changes in the M2 block and G93 block are the most significant. When CO₂ was injected simultaneously, the average contact angles of blocks M2, Z401, S123, and G93 changed by 11.29°, 10.28°, 4.92°, and −8.62°, respectively. M2 had the largest change in contact angle, while S123 has the smallest, but there was no significant change in wettability. When N₂ was injected simultaneously, the average contact angles of blocks M2, Z401, S123, and G93 changed by 11.05°, −0.18°, 4.82°, and −8.80°, respectively. Among them, M2 had the largest change in contact angle, Z401 had the smallest, and there was no significant change in wettability. When natural gas was injected simultaneously, the average contact angles of blocks M2, Z401, S123, and G93 changed by 19.18°, −5.50°, 7.10°, and 15.30°, respectively, and almost increased to a certain extent. M2 had the largest change in contact angle, while Z401 had the smallest. However, the rock reservoir remained hydrophilic. When CO₂ was selected, the changes in the M2 block and Z401 block were the most significant. The M2 block had relatively more developed macropores, better pore sorting, and a better average

pore radius and throat radius than other blocks. Therefore, injecting the medium had a more significant impact on it. The Z401 block has well-developed macropores and small pores, with the best pore connectivity, resulting in a better CO₂ injection effect. Overall, it can be concluded that the reservoir where the rock samples in the four blocks are located is a water wet reservoir. After saturating with three types of pressurized energy supplement media, it has a certain impact on the contact angle of the rock samples.

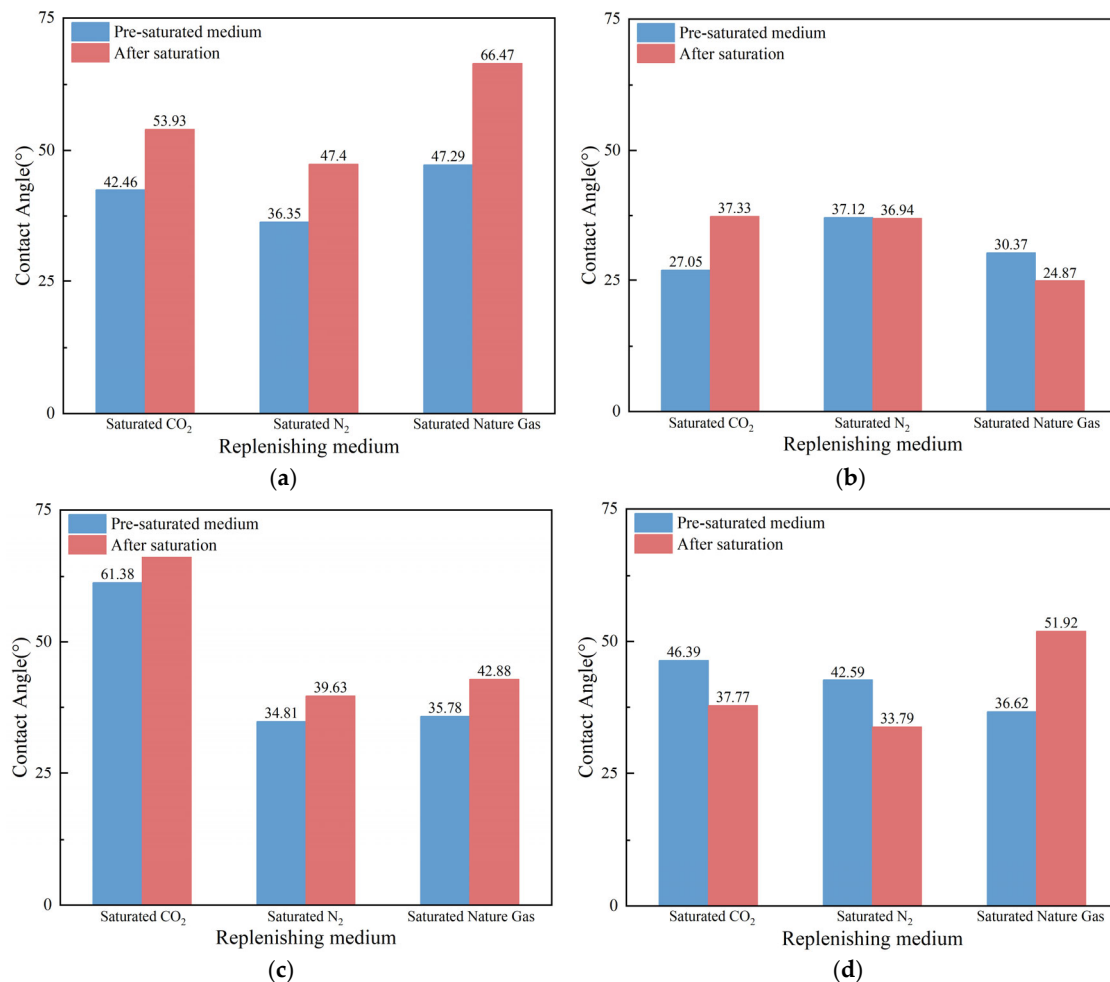


Figure 3. Changes in contact angle before and after saturation of the medium in each block. (a) M2; (b) Z401; (c) S123; (d) G93.

We analyzed the mechanism of wettability improvement in tight reservoirs with different pore structures after injecting energy supplement media. ① Mineral dissolution and surface cleaning effects were observed. After the surface was dissolved by carbonic acid, carbonate minerals such as calcite and dolomite, as well as clay minerals such as kaolinite, were exposed; ② There was an improvement in interface properties and a reduction in the interfacial tension between natural gas and CO₂; ③ The pore structure was optimized, surface substances were dissolved by carbonic acid, small pore throats were enlarged, and there was a reduction in the pore throat ratio.

Overall, the M2 and G93 blocks have the greatest impact, the rocks still exhibit hydrophilicity, and the properties of the reservoirs in each block have not changed.

3.2. Energy Supplement Medium

The impact of different energy supplements media on the changes in the wettability of various reservoirs is compared, as shown in Figure 4. The results indicate that when

considering the injection of different media with the same lithology, CO₂ and natural gas have a significant effect on increasing the wetting angle of the four blocks, with natural gas having a more significant impact on M2 and G93. Natural gas has high fluidity, low viscosity, and good injectability. Although the affected volume is limited by its low viscosity and high fluidity, the overall effect is good. The contact angle of the rock samples in Block M2 changed the most before and after saturation with natural gas, and the wettability of the rock samples changed from strong hydrophilicity to weak hydrophilicity. When the rock sample is saturated with CO₂, the increment is also significant, with a 27% increase in the wetting angle. Due to the low viscosity and high fluidity and solubility of CO₂, the injection affects a larger volume, resulting in more obvious changes. Compared to the change in contact angle caused by CO₂, N₂ has a smaller effect on the contact angle of rock samples because N₂ has a smaller molecular weight, better flowability and injectability, but a relatively lower swept volume, resulting in lower effectiveness than CO₂. The pore connectivity of G93 is the worst and the densest due to its high capillary force, poor oil displacement effect, the lower miscibility of CO₂ and oil, and small change in wetting before and after. Therefore, when the rock sample is saturated with CO₂, the average change in the contact angle is relatively small. Despite this, the rock samples in this block still maintain strong hydrophilic properties after being saturated with these three media, without significant changes in wettability. Overall, the contact angle and wettability of the same rock type exhibit different characteristics when saturated with different media. CO₂ and natural gas have a greater effect on increasing the wetting angle of the four blocks, with natural gas having a more significant effect, but overall maintaining its hydrophilic characteristics.

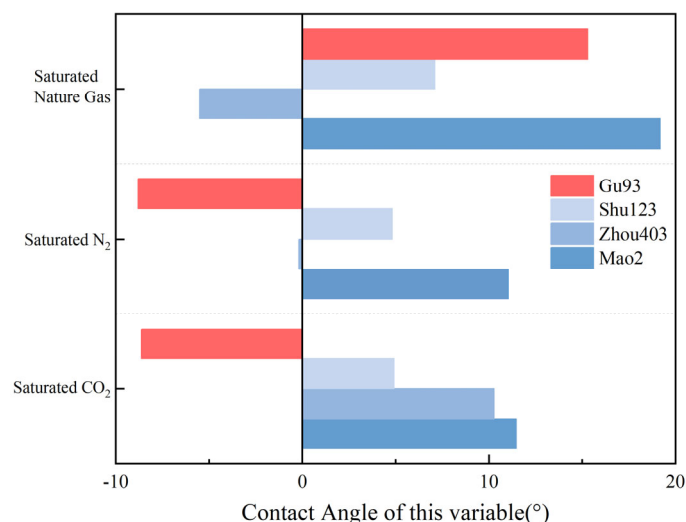


Figure 4. The change in contact angle caused by different media.

Emphasis is placed on analyzing the anomalous phenomenon of wetting angle, namely the negative increase in the peak area after CO₂ injection. One reason for this is that CO₂ dissolves in formation water to form carbonic acid (H₂CO₃), which dissolves carbonate minerals (such as calcite) or clay minerals, leading to the expansion of some micropores (increased porosity). Excessive dissolution may damage the pore skeleton, which causes local collapse or particle migration; then, the throat blocked and the effective connectivity of the pore space decreased, leading to a decrease in the NMR signal intensity.

A comprehensive analysis showed that the reservoirs in which the rock samples of the four blocks are located generally exhibit water wet characteristics. When these rock samples were saturated with three different pressurized energy supplement media, although these media had a certain degree of influence on the contact angle and pore water absorption

of the rock samples, these effects did not change the inherent hydrophilicity of the rock samples. In other words, even after being disturbed by these external media, the rock samples in each block still maintained their original water wet reservoir properties and did not undergo fundamental changes. This indicates that in terms of the wettability of tight reservoirs, whether it is changing the lithology or the medium, the characteristics of water wettability have relative stability and persistence, and are not easily significantly changed by external conditions.

4. Conclusions

The proportion of Type-II tight oil reserves in the periphery of Daqing is 42.7%, which is an important replacement resource. Due to its unique small pore throat structure, the development of fracturing is the main reservoir modification method. During the fracturing and flowback period, single oil recovery, the fracturing fluid, formation water, and oil flow in multiple phases, and the wettability of the reservoir directly affects the development effect; and the influence of the replenishment medium on the wetting angle is the basis for EOR at the stage of secondary oil recovery.

- (1) The typical pore throat structure characteristics of tight Type-II reservoirs have been clarified, with matrix minerals (quartz + feldspar) accounting for over 90% and good initial hydrophilicity. However, the Z401 block has the most developed pores, relatively good pore connectivity, and the greatest contribution to permeability. The M2 block has relatively developed large pores, with a better average pore radius and throat radius than other blocks, and better pore sorting. The pore development in blocks S123 and G93 is poor, with a small average pore volume and poor connectivity between pores.
- (2) The influence of the pore throat structure on wettability is as follows: the reservoir where the rock samples in the four blocks is located is a hydrophilic reservoir, with a minimum in situ wetting angle of about 27° in the ancient G93 block, while the other blocks have a wetting angle of $37\text{--}40^\circ$. After energy supplementation, the changes in the M2 and G93 blocks are the greatest, but they still belong to a hydrophilic reservoir.
- (3) The results of the influence of different energy replenishment media are as follows: natural gas has the greatest impact on wettability, which is due to its similar solubility to the oil phase. After adsorption, the interface characteristics are changed, and the changes are most significant; CO_2 is the second largest and N_2 has the smallest change amplitude, which is due to the mixing mechanism between CO_2 and crude oil causing a significant change in wettability. Natural gas is mainly adsorbed on the surface of rocks, and the change in surface properties combined with the theory of similar solubility increases the wetting angle; CO_2 is mainly used for interface cleaning, improving the pore throat structure and altering wettability. Therefore, considering the injection cost, we recommended prioritizing the use of CO_2 to supplement the formation energy.
- (4) Presently, the mainstream method for studying wettability is to use industry standards, but the differences in reservoir formation and the pore throat structure between tight oil and conventional oil reservoirs are huge. Therefore, using industry testing standards under micro nanopore throat conditions may have certain limitations. In addition, experiments on the core slice are destructive, and parallel experiments still need further exploration.

Author Contributions: Conceptualization, D.Y.; methodology, C.L.; software, C.L.; validation, C.L.; formal analysis, D.Y.; investigation, C.L.; resources, D.Y.; data curation, D.Y.; writing—original draft preparation, C.L.; writing—review and editing, C.L.; visualization, C.L.; project administration, D.Y.; funding acquisition, D.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This work is funded by the ministry of science and technology of the people's Republic of China, and the name of the project is “Demonstration Project for Development of Dense Oil in Jiyang Depression, Bohai Bay Basin (2017ZX05072)” of national science and technology major special project and the National Natural Science Foundation of China (No. 12272350).

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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