Analyzing the wettability of tight sandstone of Taiyuan Formation in Shenfu block, eastern margin of Ordos Basin

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Abstract. Reservoir wettability is an important indicator in the study of multiphase fluids in oil reservoirs. It involves the migration of crude oil from source rocks to reservoirs, accumulation in the reservoirs, and the entire process of crude oil development. The distribution characteristics of the wettability of sandstone reservoirs can provide a certain reference for the analysis of tight sandstone oil migration and accumulation mechanisms, and the exploration and development of tight sandstone reservoirs. This paper measures the contact angle between oil and tight sandstone by using the hanging drop method. Using the KRUSS DSA100S video optical contact angle measuring instrument, 25 unwashed oil tight cores and 62 washed oil tight cores are tested, respectively. Experimental analysis shows that the contact angle of the tight sandstones of the Taiyuan Formation in the Shenfu block of the Ordos Basin ranges from 50° to 150°, and the sample contact angles are concentrated between 70° to 110°. The wettability of the reservoir is mainly of the intermediate wet type, followed by the water wet type and the oil wet type.

1. Introduction
The Shenfu exploration block is located on the eastern edge of the Ordos Basin. The terrain is high in the east and low in the west, high in the north and low in the south. The block area is 2998.4km². The regional strata lacks Devonian and Lower Carboniferous strata, which are divided into Carboniferous Benxi Formation, Taiyuan Formation, and Permian Shanxi Formation from bottom to top (Table 1).

| Stratigraphic unit | Thickness, m | Lithology |
|-------------------|--------------|-----------|
| System | Series | Group |  |
| Permian | Lower | Shanxi Formation | 87−130 | Gray-white siltstone, fine-coarse sandstone, gray-black sandy mudstone and black coal seam |
| | | Taiyuan Formation | 33−76 | Shale, siltstone mudstone, coal seam, mudstone and sandstone interbedded, micrite limestone and bioclastic limestone |
| Carboniferous | Upper | Benxi Formation | 51−70 | The upper part is fine-coarse-grained quartz sandstone, siltstone, gray-black mudstone and coal seams; the lower part is gray sandy mudstone, thin fine sandstone intercalated with thin coal seams, bauxite mudstone, and the bottom |
According to the sedimentary sequence and lithology combination, the Taiyuan Formation is divided into upper and lower sections:

Tai 2 Member: The layer thickness is 12-50m, from the top of the 8# and 9# coal seams to the bottom of the ramp limestone or the marine mudstone of the equivalent layer. It is sandwiched by a set of gray-black mudstone, siltstone and fine sandstone. Gray-black-dark gray bioclastic limestone, micrite bioclastic limestone and coal seams. The Qiaotou sandstone in this section is at the bottom, and the sand bodies are mostly in a positive order vertically, and are the main gas-bearing sand bodies of the Taiyuan Formation.

Tai 1 Member: The layer thickness is 20-50m, the developed stable ramp limestone is an important marker layer, and the Beichagou sandstone is the top boundary. If the Beichagou sandstone is not developed, the stable dark gray mudstone is used as the top boundary. The lithology is composed of gray-black micrite bioclastic limestone with gray-white fine-coarse sandstone, siltstone, and coal seams.

Wettability refers to two immiscible fluids, the tendency of one liquid to extend along the solid surface or the affinity of particles to another liquid. The wettability is an important factor that controls the fluid mobility in the micropores, determines the oil (gas) water mobility, and affects the water drive efficiency, bound water saturation and capillary force. To a large extent, wettability determines the gas and water content of the reservoir, which in turn affects the development potential of oil and gas resources.

The wettability quantitative methods include USBM method, Amott method, contact angle method, and nuclear magnetic resonance relaxation method. The contact angle method is the most direct and common method for evaluating wettability. The Amott method evaluates the wettability of rocks based on the water and oil displacement of the rock. The centrifuge method (USBM method) uses the same rock sample to compare the area enclosed by the capillary pressure curve formed during the oil flooding and water flooding processes to evaluate the wettability. Qualitative wettability methods include atomic force microscopy, dynamic Wilhelmy plate method, Zeta potential method, and relative permeability curve method. At present, the commonly used methods for evaluating reservoir wettability include contact angle measurement and self-priming displacement method. For the self-priming displacement method, the measured wettability is only a statistically average characterization, and the test period is long. The self-priming displacement method is not suitable for the wettability measurement of tight cores. The principle of the contact angle method is relatively simple, the measurement process is convenient to operate, and the result is more intuitive. Therefore, this paper uses the contact angle method to measure the tight sandstone of Taiyuan Formation in Shenfu block.

2. Experimental materials and methods

2.1. Experimental equipment
When the droplet is in contact with the solid plane, its shape depends on the relative size of the interfacial tension and adhesion force. In the equilibrium state, the tangent line is drawn from the junction of the three phases along the edge of the droplet, and the angle formed with the solid surface is the contact angle. The size of the contact angle can characterize the wettability of the solid surface. This paper uses the hanging drop method in the contact angle method to measure the contact angle between oil and tight sandstone, as shown in Figure 1.
According to the formation water characteristics of the sampling interval, the corresponding experimental water samples are configured, and the oil is titrated from bottom to top in the water environment. After the oil droplets are in stable contact with the tight sandstone surface, the contact angle is measured to obtain tight sandstone wetting results for oil. According to the petroleum industry standard, when the contact angle $\theta$ is between 0 and 75°, it is water wet; when it is between 75° and 105°, it is intermediate wet; when it is between 105° and 180°, it is oil wet.

The test instrument is a KRUSS DSA100S video optical contact angle measuring instrument, which includes two parts: an optical system and a data measurement system. Among them, the data measurement system is controlled by a computer, and liquid titration is performed through a micro syringe. The optical system can record the image of the droplet and automatically analyze the shape of the droplet. We manually adjust the baseline according to the contact form of the droplet and the rock interface, and select the appropriate fitting method, to measure the contact angle of the core surface.

2.2. Experimental materials

In this paper, 25 unwashed oil cores and 62 washed oil cores of 39 wells in Taiyuan Formation in Shenfu block are selected for wettability measurement experiments. The core samples are 2.5cm in diameter and 0.2cm in thickness.

Experimental oil sample A is industrial oil 3# white oil, and oil sample B is crude oil from the Taiyuan Formation in the Shenfu block (Table 2).

| Sample       | Saturated hydrocarbon content, % | Aromatic content, % | Gel content, % | Asphaltene content, % | Density, g/cm³ | Viscosity, mPa·s |
|--------------|---------------------------------|--------------------|----------------|------------------------|----------------|-----------------|
| Oil sample A | 99.9                            | 0.1                | 0              | 0                      | 0.787          | 1.2             |
| Oil sample B | 60.8                            | 22.3               | 9.2            | 2.9                    | 0.946          | 335.9           |

According to the formation water properties of the Taiyuan Formation in the Shenfu block, pure NaCl, CaCl₂, MgCl₂ and other reagents are used to prepare the experimental water samples. The chemical composition and physical properties are shown in Table 3.

| Ion concentration, g/L | Salinity, g/L | Density, g/cm³ | pH |
|------------------------|---------------|----------------|----|
| Na⁺ 10.5                | 33.7          | 1.052          | 6.7 |
| Ca²⁺ 1.8               |               |                |    |
| Mg²⁺ 0.4              |               |                |    |
| Cl⁻ 20.9             |               |                |    |

2.3. Experimental method

The experiment mainly includes: (1) Measuring the contact angle of 25 unwashed oil cores; (2) Measuring the contact angle of 62 washed oil cores under different conditions. The steps are as follows:

①Before the experiment, the core sample is processed into a flat plate with a thickness of about 0.2cm, and the surface is polished to eliminate the influence of roughness on the contact angle;

②The sample tank is filled with the prepared water sample, and the sample to be tested is completely immersed for about 36 hours;
According to the analysis and calculation of the geological data of the selected block, the formation temperature is about 57°C. In order to make the measured wetting angle as close as possible to the formation conditions, the experimental temperature is set to 57°C and the water bath is kept constant;  

After the soaking is complete, a micro syringe is used to inject a drop of oil, the volume of the oil drop is about 1 ~ 2 µL, and the contact state of the oil drop with the rock surface can be observed;  

After the oil droplet-water-core sample is stable for about 12 hours, the droplet is magnified and photographed by the optical system, and the contact angle of the core sample is measured;  

Different positions for each sample are chosen to perform 3 measurements and the average value can be derived;  

In the experiment of restoring the wettability of oil reservoir and studying the influence of not using oil sample on the wettability of tight sandstone, it is necessary to clean the core and place it in the corresponding oil sample for crude oil aging. The aging temperature and time are respectively, 57°C (Formation temperature) and 7 days. After cleaning the aged core, we immerse the core in the prepared experimental water sample for 48 hours, repeat the above contact angle measurement steps until all experiments are completed.

3. Results and analysis

3.1. The wettability characteristics of unwashed oil tight sandstone samples

The 25 tight sandstone samples with unwashed oil are numbered samples 1 to 25 respectively. According to the contact angle measurement results (Figure 2), it can be seen that the contact angle of unwashed oil tight sandstone ranges from 20° to 50°, all belonging to water wet.

![Figure 2. Contact angle results of unwashed oil sample.](image)

According to the statistical results of the oiliness of unwashed oil tight sandstone samples, among the 25 unwashed oil tight sandstone samples, there are 11 tight sandstone samples with oil traces, 6 tight sandstone samples with oil spots, and 8 tight sandstone samples with oil leaching grade.

According to the contact angle measurement results of samples with different oil-bearing grades, it can be found that the oil-bearing grades of tight sandstone samples with oil traces have contact angles ranging from 22° to 42°, with an average of 30.16°. For the oil-bearing grades of tight sandstone with oil spots, the contact angle distribution range is between 24° and 36°, and the average value is 29.68°. If the oil-bearing grade of tight sandstone samples is oil immersed, the contact angle distribution range is between 24° and 46°, and the average value is 30.56°. Tight sandstone samples of different oil-bearing grades have little difference in contact angles, and they are distributed in the interval of 20°-40°, indicating that there is no obvious correlation between the wettability and oil-bearing properties of tight sandstones. The reason could be that the wettability of tight sandstone reservoirs is affected by external fluids during drilling. Zhuang Yan et al. pointed out that the drilling fluid invaded tight sandstone reservoirs during the sampling process, causing the tight sandstone surface to contact the water in the drilling fluid. The salinity of the reservoir fluid changed, the content of inorganic salt ions increased,
and the adsorption is enhanced, causing the wettability of the reservoir to become increasingly hydrophilic. In addition, the storage conditions of tight sandstone samples are poor. The time interval between the sample retrieval and the contact angle measurement experiment is too long. The crude oil on the surface has been volatilized. The measurement results more reflect the wettability of the surface minerals of the tight sandstone samples.

3.2. The wettability characteristics of washed oil tight sandstone samples

The wettability of the 62 washed oil tight cores before and after aging are measured by contact angle method. The aging oil is oil sample B. The samples are numbered from 1 to 62. As shown in Figure 3, the contact angle distribution range of the 62 washed oil samples before aging is in the range of 25° to 50°, and the contact angle is unevenly distributed and wetted. Similarly, the contact angle results of 62 samples of washed oil tight sandstone after oil sample B aging are calculated. As shown in Figure 4, the contact angle distribution ranges from 55° to 150°. The size distribution is uneven, and the wetting types include water wetting, intermediate wetting, and oil wetting.

Comparing the contact angle data of 62 samples of washed oil tight sandstone before and after aging, it can be found that after oil sample B aging, the contact angle value increases, and the distribution trend remains the same as before aging, which shows that the aging of crude oil can change the contact angle of tight sandstone and transform its wettability from water-wet type to intermediate-wet type and oil-wet type.

According to the change in contact angle of each sample before and after aging, the increase in contact angle ranges from 20° to 100° after oil sample B aging, indicating that the wettability of crude oil to different tight sandstone samples changes to different degrees. The appearance of this phenomenon may be due to the complex and diverse mineral components of tight sandstone. After reacting with crude oil, some show hydrophilicity, and some show lipophilic or neutral wetting.

The wet type of the 62 washed oil tight sandstone samples after oil sample B aging is counted. There are 19 water wet samples, 37 intermediate wet samples, and 6 oil wet samples, indicating that after oil sample B aging, 37 samples changed from water wet to intermediate wet type, and 6 samples changed
from water wet to oil wet. The injection of crude oil made the wettability of tight sandstone change to the intermediate wet type.

4. Conclusion
(1) To study the wettability characteristics of tight sandstone reservoirs, it is necessary to restore the original conditions in the reservoir state as much as possible. In this paper, unwashed oil samples are selected for wettability evaluation experiments. The experimental results show that there is no correlation between the oil grade and wettability of 25 unwashed oil tight sandstone samples. The contact angle of tight sandstone samples after crude oil aging is measured at the reservoir temperature, reflecting the wettability of the tight sandstone reservoir under the conditions closest to the real reservoir.

(2) The contact angle of tight sandstone after crude oil aging reflects the change of the wettability of the reservoir by the entry of crude oil under the real reservoir state. According to the statistical results of contact angles, the overall wettability of the tight sandstone reservoirs in the Shenfu block of the Ordos Basin is characterized by the intermediate wet type, followed by the water wet type and the oil wet type.

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