Research on the Relationship between Electrical Parameters and Relative Permeability of Tight Sandstone

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ABSTRACT: The relationship between the electrical properties and relative permeability of tight sandstones with complex pore-throat structures is still unclear. In this study, a relationship model between the electrical parameters and pore-throat structure and the relative permeability of tight sandstone based on experimental data was established by combining theoretical derivation and experimental comparison. The model has typical three-terminal element characteristics. Porosity had little effect on relative permeability, whereas saturation index had a significant control effect on relative permeability. The relative permeability curve deduced based on the electrical parameters was quite different from the experimental fitting curve. Because irreducible water could conduct electricity but not flow, the relative permeability of the gas phase derived from the theory was higher than the experimental one, while the relative permeability of the water phase was lower. The isotonic point saturation of the phase permeability curve derived from the rock electrical parameter theory was larger than that obtained from the experiment. This research could help us obtain accurate relative permeability curves through electrical parameters and provide a basis for the fine evaluation of tight sandstone two-phase flow.

1. INTRODUCTION

The electrical properties and relative permeabilities of rocks are two basic characteristics in the process of multiphase seepage in porous media. They are widely used in the distribution of remaining oil and gas in multiphase seepage processes, resistivity logging interpretation, underground oil and gas seepage law, reservoir evaluation, and oil and gas exploitation.1–5 At present, the electrical parameters of rock are mainly obtained by the Archie formula. The formation factors and electrical characteristic values, such as the resistivity increase coefficient, are obtained by the changes in water saturation and resistivity. However, an increasing number of studies have shown that the electrical properties of rocks not only depend on the changes in sample water saturation and resistivity but also on the characteristics of rock pore structure, pore throat distribution, mineral composition, and relative permeability of multiphase flow.6–8 Relative permeability is defined as the relative ability of multiphase flow through pores in porous media, which can be considered as the macroscopic characterization of the microscopic pore throat structure on the seepage law of multiphase flow. Although the importance of relative permeability in reservoir research is well known,9,10 the understanding of the relationship between relative permeability and rock electrical properties in the process of two-phase flow is still very limited, especially in tight sandstone with a complex micropore throat structure.

Ma et al.3 established the relationship between rock resistivity and permeability. The authors obtained the power function relationship between permeability K and R^0 inverse of resistivity using resistivity to calculate rock permeability. Subsequently, Liu et al.11 established the corresponding relationship among porosity, permeability, resistivity, and spontaneous potential logging curves to perform an inversion calculation of the reservoir physical parameters. It solves the practical problems of reservoir evaluation caused by incomplete reservoir parameters in the process of geological fine research. Previous studies on the influence of the micropore structure of tight sandstone gas reservoirs have mainly focused on the electrical properties and permeability of rocks. Compared with these two aspects, the relative permeability of gas–water can reflect the gas–water migration law and residual gas distribution state in real micropore structures.12–15 The results showed that the relative permeability, water saturation, and residual gas–water distribution are closer to real gas well production. Ma et al.16 established
Table 1. Basic Physical Properties of Samples in the Study Area

| Sample name | Sample length (cm) | Sample diameter (cm) | Dried sample weight (g) | Sample porosity (%) | Kirschner correction permeability (%) | Average value of pore throat radius (µm) | Hydraulic radius (µm) |
|-------------|--------------------|----------------------|-------------------------|---------------------|--------------------------------------|----------------------------------------|----------------------|
| H1          | 5.00               | 2.520                | 64.365                  | 4.56                | 0.0602                                | 0.4561                                 | 1.349                |
| H2          | 4.953              | 2.518                | 60.984                  | 5.926               | 0.0418                                | 0.6598                                 | 1.401                |
| H3          | 4.582              | 2.512                | 58.213                  | 5.0216              | 0.0721                                | 0.6302                                 | 1.549                |
| H4          | 4.602              | 2.520                | 57.286                  | 6.4098              | 0.0329                                | 0.6220                                 | 1.602                |
| H5          | 5.200              | 2.522                | 62.368                  | 9.3682              | 0.0671                                | 0.4011                                 | 1.301                |
| H6          | 4.620              | 2.510                | 55.100                  | 8.467               | 0.1138                                | 0.4528                                 | 1.100                |
| H7          | 5.00               | 2.52                | 65.020                  | 3.16                | 0.0994                                | 0.5068                                 | 1.443                |
| H8          | 4.984              | 2.528                | 63.02                   | 5.7092              | 0.0231                                | 0.5469                                 | 1.071                |
| H9          | 5.350              | 2.520                | 66.318                  | 5.7012              | 0.0688                                | 0.4040                                 | 1.730                |
| H10         | 4.986              | 2.520                | 64.823                  | 6.7162              | 0.0158                                | 0.4820                                 | 1.260                |
| H11         | 5.000              | 2.520                | 61.316                  | 7.7                 | 0.0631                                | 0.4248                                 | 1.318                |
| H12         | 4.460              | 2.450                | 51.300                  | 10.8638             | 0.0780                                | 0.5138                                 | 1.051                |

A calculation model for calculating the relative permeability of gas and water phases from the resistivity index based on the Poiseuille formula and Darcy law. The influence of bound water on the electrical properties and relative permeability of rocks is discussed for the first time. Irreducible water is negligible in the Poiseuille formula, but it is essential to calculate the resistivity parameters. This is because the irreducible water may not flow in a two-phase flow but can conduct electricity.17–21 The model provides theoretical support for the study of the relationship between rock electrical properties and relative permeability. However, whether the theoretical model is suitable for the study of the response law of rock electricity and relative permeability in tight sandstone gas reservoirs with complex pore-throat structures has not been verified experimentally. Based on the results of previous studies,16–21 we found that the formation factors and resistance increase coefficients are all functions of pore structure parameters in the process of tight sandstone multiphase flow.

To further clarify the relationship between the electrical properties and relative permeability of rock under the microscopic pore structure parameters of tight sandstone, based on the findings of previous research, this study compared the theoretical model of relative permeability based on the electrical parameters of rock and the experimental model of relative permeability based on experimental data fitting.18–20 The functional relationships among the pore structure index, formation factors, resistivity increasing coefficient, pore throat tortuosity, pore throat radius, permeability, and relative permeability were derived. The micropore structure of tight sandstone gas reservoir samples was analyzed, and the relationship between the electrical properties and permeability of the rock was further studied. Finally, the effects of physical parameters on the rock electrical parameters and gas–water phase permeability characteristics are discussed, and the reasons for the difference between the standardized relative permeability curve obtained experimentally and the relative permeability curve derived by electrical function theory are discussed.

2. THEORETICAL MODEL DERIVATION

According to Archie’s formula, formation factor $F$ and resistance increase coefficient $RI$ are the basic parameters of the rock electrical properties, which can be expressed as a function of porosity $\Phi$ and water saturation $S_w$. The Archie formula that is currently widely used is as follows:

$$ F = \frac{R_0}{R_w} = a\Phi^m $$

(1)

$$ RI = \frac{R_w}{R_0} = bS_w^{-n} = b(1 - S_b)^{-n} $$

(2)

where $a$, $b$, $m$, and $n$ are basic parameters of rock electricity; $a$ and $b$ are lithology coefficients, $m$ denotes the cementation index, and $n$ represents the saturation index. In this paper, saturated brine $R_0$ with different salinity and resistivity $R_i$ of sandstone with different water saturations are used to calculate the values of rock electrical parameters $a$, $b$, $m$, and $n$. Through Archie formula (eqs 1 and 2), the relationship between different water saturation $S_w$ and porosity $\Phi$ can be determined as follows:

$$ S_w = \frac{abR_w}{\Phi^m R_i} $$

(3)

In this study, the relationship between different water saturation $S_w$ and different water content sandstone resistivity $R_i$ in the range of saturation $\Phi$ was obtained using this formula.

2.1. Relationship between Microscopic Pore Structure and Electrical Characteristic Parameters. The pore throat radius $r$ and tortuosity $\tau$ are characteristic parameters of the micropore structure. The pore-throat radius is a measure of the size of porous media, which is convenient for studying the seepage characteristics of porous media. In previous studies, the pore shape of porous media was simplified into circular, elliptical, triangular, hexagonal, and rectangular shapes.26–28 For a better evaluation of the macroscopic transport properties of rocks, this study simplified the pore shape of the porous medium to a circular capillary. According to the average pore radius and pore throat tortuosity formula obtained by the capillary bundle model,29 we obtain the following:

$$ S_w = \frac{\Phi^m \tau r^{-2}}{ab\pi} $$

(4)

Equation 4 establishes the functional relationship among the pore-throat radius, tortuosity, and rock electrical parameters ($a$, $b$, $m$, $n$) at different water saturation. When the porous medium was 100% saturated with brine, $S_{wV}$ was equal to 1. The relationship among pore throat radius $r$ and pore throat tortuosity $\tau$, electrical parameters of rock ($a$, $b$, $m$, and $n$), and pore structure index $M$ can be expressed as follows.
The functional relationship between permeability and electrical parameters was obtained by Li et al., combined with the Poiseuille equation and rock electrical parameters was obtained as follows

\[ K = \frac{1}{8\pi} d^{-3/2} \Phi^{b+1/2} \]  

(8)

2.2. Relationship between Permeability and Electrical Properties. According to the relative permeability obtained by Li et al., combined with the Poiseuille equation and Darcy’s law, the relationship between the relative permeability and electrical characteristic parameters is as follows

\[ K_{rw} = \frac{1}{R_l} \sqrt{\frac{abR_w}{\Phi m R_1}} \sqrt{\pi^2 + m \pi^2} \]  

(9)

3. EXPERIMENTAL METHOD

3.1. Sample Preparation and Physical Characteristics. The physical properties of the reservoir are the macro parameters of the micropore-throat structure characterization. In the experiment, a White Stone porosity and permeability meter was used to measure the selected 12 samples, and the basic physical property parameters of the reservoir, such as porosity and permeability, were obtained (Table 1). The porosity \( \Phi \) (measured by the nitrogen peripheral pressure) ranged between 4.3 and 11.2%, with an average value of 6.684%. Permeability \( K \) (measured by confining pressure of 3 MPa) varied from 0.01 to 0.15 mD, with an average of 0.0635 mD. The macroscopic physical properties of the reservoir indicated that the reservoir is a low-porosity and low-permeability tight reservoir. The porosity and permeability parameters of the 12 samples were fitted, and the index fitting relationship between \( \Phi \) and \( K \) was obtained as \( K = \varepsilon \Phi \), and the fitting coefficient \( \varepsilon \) was 0.0021. The correlation fitting degree is not high, with a poor correlation between porosity and permeability; however, the heterogeneity is strong, so it is a low-porosity and low-permeability heterogeneous tight sandstone reservoir (Figure 1).

3.2. Analysis of the Characteristics of the Micropore Structure. Thin section analysis, scanning electron microscopy (SEM), capillary pressure curve analysis, and X-ray diffraction (XRD) experiments were conducted on the selected 12 cores. The thin section and SEM images of the samples are shown in Figure 2. The main rock type is feldspar lithic sandstone, and the secondary dissolution pores are the main rock type. The pore types are diversified, with a pore diameter of 0.015–0.35 mm, and the main pore throat was punctate (Figure 2a–d). The core was relatively dense, where the compact effect led to almost no development of the particle space. The illite and smectite mixed layer are mainly filled in intergranular pores, and feldspar particle fracture and clastic particle dissolution form micropores (Figure 2e–h). This microstructure is mainly related to the deposition of delta front subfacies and ancient land source control in the study area. The main mineral components are quartz (50.6%), potash feldspar (12.1%), plagioclase (19.3%), and clay minerals (12.9%) (Figure 3).

Mercury injection technology is a quantitative testing technology for monitoring the microstructural characteristics of tight oil reservoirs. The capillary pressure curve was tested using the high-pressure mercury injection semipermeable diaphragm method. According to the Washburn equation,

\[ P_c = \frac{2\sigma \cos \theta}{r} \]  

(10)

When the displacement pressure exceeds a certain capillary pressure, mercury overcomes the capillary pressure and enters the pores. In eq 10, \( P_c \), \( r \), \( \sigma \), and \( \theta \) denote capillary pressure, pore throat radius, surface tension, and mercury contact angle, respectively. The Washburn equation and the equivalent ball model were obtained, along with the variation of the sample gauge pressure with the aperture saturation degree.

3.3. Theoretical and Experimental Studies on Electrical Property Measurement of Tight Sandstone. The electrical measurement of rock is an important experimental method for evaluating oil and gas saturation in logging interpretation. According to the analysis of the micropore-throat structure characteristics, the physical properties of sandstone in the study area are characterized as poor (average porosity 6.6684%, permeability 0.0635 mD), with a complex pore-throat structure and strong microheterogeneity (Figure 1). To obtain the electrical characteristic parameter values \( (a, b, m, \text{and } n) \) of the samples under different water saturation states, we conducted a rock electrical property measurement experiment on the selected samples.

This experiment mainly used the MD-II capillary pressure and an electrical connection tester. The capillary pressure curve was measured using the semipermeable baffle method. The experimental device mainly includes a nitrogen cylinder, balance, resistivity measuring instrument, III hand pump, semipermeable diaphragm, capillary pressure electrical measuring instrument, and data acquisition PC.

The selected samples were cleaned and dried at 60 °C for 48 h until the weight no longer changed. The samples were vacuumed and pressurized to saturate the water (vacuumed for 4 h and then pressurized for 20 MPa), and the saturated weight of the

Figure 1. Sample porosity–permeability relationship fitting diagram.
sample was obtained. The water had a concentration of 30000 ppm and a viscosity of 1 MPa·s. The saturated sample was loaded into the core holder and connected according to the experimental device diagram shown in Figure 4. The confining pressure was increased to 6 MPa using a hand pump. The digital bridge measures the resistivity of saltwater at a standard temperature, $R_w$. The resistivity of the sample in the 100% saturated brine was $R_0$. Nitrogen was injected into the core with a constant pressure difference of 2.5 MPa, and the core resistivity $R_t$ at different water saturation was measured and recorded.

3.4. Theoretical and Experimental Study on Relative Permeability Measurement of Tight Sandstone. The gas–water relative permeability test device is shown in Figure 5. It is mainly composed of a pressure supply system and measuring and metering systems. The pressure supply system mainly includes a nitrogen bottle, gas flow meters, and a pressure transducer. The measurement system includes a core holder, nuclear magnetic resonance instrument, and a hand-cranked confining pressure pump. The metering system included a gas meter, drying flask, and precision electronic balance. The specific steps were as follows. (1) To eliminate the influence of residual gas in the samples on the experimental results, the

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**Figure 2.** (a–d) Thin section and (e–h) scanning electron microscopy images.

**Figure 3.** Quantitative map of sample mineral content.

**Figure 4.** Diagram of rock electric experiment device.
selected samples were vacuumed and pressurized to saturate the formation water (concentration of 30 000 ppm, with viscosity and density of 1 mPa·s and 1.0128 g/cm³, respectively) to more than 98%. (2) The saturated sample was placed in the core holder. The instruments were connected according to the experimental setup shown in Figure 5. The sample after the saturated water sample was scanned for the $T_2$ spectrum. (3) The confining pressure pump was shaken so that the confining pressure was increased to 5 MPa and maintained. After selecting the appropriate displacement pressure difference, the unsteady-state method was used to perform the gas flooding experiment. The choice of displacement pressure difference directly affects the value of the irreducible water saturation. If the displacement pressure is too small, the gas cannot overcome the capillary resistance and displace the water in the tight sandstone pores. If the displacement pressure is too high, a viscous fingering channel is formed, and the irreducible water saturation will be high. Therefore, the key to the success or failure of an unsteady gas flooding experiment is to choose the appropriate displacement pressure. At present, there is no suitable formula to obtain the displacement pressure difference in gas flooding experiments. We referred to the pressure difference value obtained in previous studies and used the empirical formula (11) to obtain the displacement pressure difference required for this experiment.\[\Delta p = \epsilon \times 0.00167 \times \sigma_{gw} \times \sqrt{\frac{\phi}{K}}\] (11)

where $\epsilon$ is the correction coefficient. Choose 0.2–0.4 according to the physical properties of the samples in this study. (4) During the experiment, the displacement time, cumulative gas production, cumulative water production, and displacement pressure difference were measured at different intervals. When the cumulative water production no longer increases or two or more continuous NMR $T_2$ spectrum curves overlap, it can be considered that the sample has reached the bound water state at this time. The weight of the sample in the bound water state was measured. All measurements in the experiment were performed at room temperature and standard atmospheric pressure ($T \approx 20 ^\circ C, P = 1\ atm$).

4. EXPERIMENTAL RESULTS

4.1. Quantitative Analysis of Microscopic Experiments. Two samples were selected to test the capillary pressure of the high-pressure mercury injection. As a result, the capillary pressure variation curve with water saturation and pore size...
distribution diagram was obtained (Figure 6). It can be seen from the capillary pressure curve that the capillary pressure in the initial section of the capillary pressure (water saturation $S_w = 100\%$) rises sharply. At this time, because the starting pressure has not been reached, mercury has not really entered the core, which belongs to the holding pressure stage. When the capillary pressure is greater than the starting pressure, mercury enters the core and enters the main displacement phase at this time. The curve was relatively flat, and water saturation dropped quickly.

As shown in Figure 6, the middle gentle section of H8 is longer than that of H10, indicating that the more concentrated the pore distribution of the H8 sample, the better will be the sorting performance and the physical properties. When the capillary pressure further increased, the drop in water saturation decreased until it reached the irreducible water state.

The distribution of the pore throat radius and permeability contribution rate were calculated from the mercury pressure experiment (Figure 7). The pore size distribution diagram shows that the pore radius of the sample H8 and H10 matrix is mainly distributed below $0.400$ and $0.25 \mu m$, respectively. The pore throat radius in the study area was relatively small, and a micropore was developed.

4.2. Analysis of Rock Electric Experiment Results. By conducting gas-driven water rock electricity experiments on 12 samples in the study area, the relationship curve between formation factors and porosity ($F−\Phi$) and that between resistance increase coefficient and water saturation ($RI−S_w$) could be obtained (Figure 8). From the relationship curve between formation factors and porosity, the obtained relationship was a straight line with a good correlation (correlation coefficient of $97.66$) in the double-logarithmic coordinate system (Figure 8a). According to the formation factor expression in Archie’s law (eq 1), $a = 1.2169$ and $m = 1.438$ can be obtained. Under double-logarithmic coordinates, the relationship between the resistance increase coefficient $RI$ and the water saturation $S_w$ function is relatively sparse, but it is not difficult to find that the $RI−S_w$ function points are mainly concentrated in a certain area (the middle area of the red line in Figure 8b). According to the resistance increase coefficient

![Figure 7. Pore-throat radius distribution: (a) permeability contribution rate of H8 and (b) permeability contribution rate of H10.](image7)

![Figure 8. Corresponding relation diagram of rock electricity: (a) relationship between formation factors and porosity and (b) relationship between resistance increase coefficient and water saturation.](image8)
expression (eq 2), it can be seen that the value range of \( b \) is 0.93—1.06 and the value range of \( n \) is 1.33—2.78.

4.3. Analysis of Relative Permeability Experiment Results. The gas—water relative permeability curve obtained using the unsteady-state gas flooding experiment method is shown in Figure 9. The classification is based on the shape of the gas—water relative permeability curve, the area of the two-phase permeation zone, the irreducible water saturation, and the relative size of the gas—water relative permeability value under irreducible water saturation. The gas—water permeability curves in the study area were divided into three categories. The relative permeability curve corresponds to the permeability of the reservoir in an actual reservoir.34—39 The tight sandstone reservoirs in the study area have poor seepage capacity, and no reservoirs with slow decay, long stable production periods, and late water breakthroughs in gas wells have been found. It can be seen from the division results of the gas—water phase permeability curves that the distribution of various types of curves is relatively concentrated, indicating that the division results are more reasonable.

The H6, H7, and H12 samples in the study area showed the characteristics of type I reservoirs (Figure 9a). The irreducible water saturation of this type of reservoir was low. The maximum relative permeability of the gas phase was higher than that of the water phase. The water saturation corresponding to the isotonic point was \( \sim 70\% \). The relative permeability curves of \( K_{rg} \) and \( K_{rw} \) were gentle and concave. This type of sample had a wide range of porosities, \( \Phi = 3.16—10.86\% \). The permeability of the sample was close to \( 0.0780—0.1138 \) mD. The average pore-throat radius was \( \sim 0.4528—0.5138 \) cm. The irreducible water saturation was 35.2—52.3%, with an average value of 41.72%. The results showed that as the water saturation increased, the relative permeability of the gas phase decreased rapidly, while the relative permeability of the water phase increased slowly. Gas reservoirs with this type of relative permeability curve feature have high initial gas recovery, late water breakthroughs, and long anhydrous gas recovery periods.
The H1, H3, and H9 samples of the research area exhibited II-type reservoir characteristics (Figure 9b). The irreducible water saturation of this type of reservoir was high. The maximum relative permeability of the gas phase was the same as that of the water phase, and the water saturation corresponding to the isotonic point was ~82%. Two relative permeability curves were presented with a concave shape and were steeper. As the water saturation increased, the relative permeability curve of the gas phase decreased rapidly. The relative permeability curve of the water phase increased rapidly, and the two-phase seepage area became narrower. The sample porosity was 4.56–5.7012%, along with an average value of 5.094%, and the penetration value was close to 0.0602–0.0721 mD. The average variant of the average pore throat was ~0.4040 to 0.6302 cm. The porosity and permeability of this type of reservoir were lower than those of type I reservoirs. Irreducible water saturation was 58.8–63.3%, with an average value of 60.8%, which is more than 20% higher than that of type I reservoirs. Gas reservoirs with this type of relative permeability curve feature have a low gas recovery and short water breakthrough time. Once a single well encounters water, a rapid drop in gas production leads to a sudden increase in water production. The stable production time is short, or there is no stable production time.

The H2, H4, H5, H8, and H11 samples exhibited type III reservoir properties (Figure 9c). The irreducible water saturation of this type of reservoir varied over a wide range. The maximum relative permeability of the gas phase was lower than that of the water phase. The range of water saturation corresponding to the isotonic point was 42.6–92.5%. The two-phase seepage area was the widest. The sample porosity was 5.7092–9.3682%, and the average porosity was 7.082%. The permeability was 0.0231–0.0671 mD, with an average value of 0.0456 mD. The average radius was 0.4011–0.6598 cm, with a mean value of 0.5309 cm. As the water saturation increases, $K_{rw}$ rises rapidly in a concave shape, and the $K_n$ curve drops smoothly. The production characteristics of actual gas reservoirs with this type are as follows: the two-phase flow time is long, and the water breakthrough time is short. After the gas well encounters water, no more gas is produced.

5. DISCUSSION

Based on the clarification of the microscopic pore-throat characteristics, electrical properties of rock, and relative permeability of tight sandstone, it is necessary to further determine the variation in the relative permeability of tight sandstone with rock electrical parameters and pore-throat structure. This provides a basis for the productivity evaluation and logging interpretation of tight sandstone gas reservoirs.

5.1. Relationship between Electrical Parameter $n$ and Relative Permeability of Samples with Different Pore-Throat Structures. Figure 10 shows the relationship between the tight rock porosity $\Phi$ and the rock electrical saturation index $n$ of the study zone. The figure presents the three-terminal element characteristics obtained by Li et al. in the tight sandstone $\Phi$–$n$ relational curve of the Ordos Basin. This experimental point was concentrated in a triangle. According to the quality of the pore structure and the classification of relative permeability, the relative permeability curves corresponding to the corresponding points are listed.

Figure 10 shows that the pore structure of type I was better and approximated. The porosity had a large variation range ($\Phi$ from 3.16% to 10.8639), and the $n$ value was relatively stable. According to the fitting diagram of the porosity–permeability relationship (Figure 1), the correlation between porosity and permeability was poor (fit factor was 0.0021). This shows that there were many isolated pores in the sample. There was no two-phase flow in this part of the pores. The shape and size of the relative permeability are controlled by not only porosity but also multiple factors such as pore space and pore structure. The type II relative permeability curve had a similar porosity ($\Phi = 5\%$) and pore structure ($n = 1.6$). The type III relative permeability curve had a large porosity ($\Phi = 5.926–9.3862\%$) with a poor pore structure. The $n$ value was generally higher than the $n$ value corresponding to the type II relative permeability curve.

The above core law presents typical three-terminal element characteristics. The experimental area at the upper left of the intersection of the porosity and saturation index generally corresponds to samples with low porosity and poor pore structure. The relative permeability curve shows typical characteristics of a type III curve. The viscous fingering characteristics of the gas–water two-phase flow process were outstanding. The gas well encounters water quickly, the water cut rises rapidly after the water breakthrough, and the gas well productivity is low. The experimental area at the bottom left of the intersection diagram generally corresponds to samples with small porosities and good pore structures. The experimental area at the bottom left of the intersection diagram generally corresponds to samples with small porosities and good pore structures. The lower right end of the intersection diagram mainly corresponds to a core with large porosity and a good pore structure. Figure 10 shows that the porosity has no obvious effect on the relative permeability, and the saturation index $n$ has a significant control effect on the relative permeability curve. The effects of the core microscopic pore structure on other electrical parameters and the relative permeability of the core, as well as the correlation between electrical parameters and relative permeability, were also analyzed. In the process of pore structure research and analysis, the effective porosity and maximum tribute saturation were selected as the actual storage capacity of the reservoir. Effective porosity characterizes the range of pores that can be stored and used for gas flow. The effective porosity reflects the effective gas storage space that can be recycled during the actual production process. The maximum storage saturation can be obtained through the mercury injection curve, which reflects the maximum total liquid storage space of the fluid. It is also one of the fundamentals for the classification of the relative permeability types in this study.

5.2. Relationship between Microscopic Pore Structure Parameters and Electrical Parameters. Movable gas porosity and pore structure index were selected to characterize the actual storage capacity of tight reservoirs in the study of microscopic pore throat structure, combined with previous experiments and theoretical derivation.28,33 The movable gas porosity characterizes the actual residual two-phase flow reservoir space43 (eq 12). The pore structure index is a comprehensive index for evaluating the microscopic pore structure of rocks. It is the average pore radius and tortuosity (reflecting the tortuosity of the pore throat of a complex porous medium, defined as the ratio of the actual flow distance of the fluid in the porous medium to the macroscopic distance length) ratio (eq 7).

$$\Phi_m = (S_0 - S_{wr} - S_{gr}) \times \Phi / 100$$

where $\Phi_m$ is the movable gas saturation (%), $S_0$ denotes the initial water saturation of the sample (%), $S_{wr}$ represents the
irreducible water saturation (%), $S_{irr}$ is the residual gas saturation, and $\Phi$ signifies the porosity of the sample gas (%).

The relationship between the movable gas porosity $\Phi_m$ and saturation index $n$, and lithology coefficient $b$ conforms to the function change law of the power index, and the degree of fit is relatively high. The greater the porosity of the movable gas in the core, the greater the storage space available for two-phase flow, along with the greater corresponding core $n$ value and the correlation coefficient $R_2 = 0.9587$. The corresponding lithology coefficient $b$ also increased with the increase in movable gas porosity, but the correlation was not high (only 0.3606). Figure 11a shows that the electrical characteristic parameters of the rock are significantly affected by the microscopic pores. The change in the saturation index $n$ is controlled by the porosity of the movable gas, and the lithology coefficient $b$ is also affected by the porosity of the movable gas. To gain a deeper understanding of the influence of the complex microscopic pore structure parameters of tight sandstone on the electrical properties of the rock and verify the accuracy of the experimental results, the relationship between the pore structure index $M$ and the formation factor $F$ and the movable gas porosity $\Phi_m$ was studied (Figure 11bc). The red color in Figure 11bc represents the experimental results of the change in the pore structure index $M$ with formation factors, while the blue color represents the theoretical value obtained through theoretical derivation (eq 7). The pore structure index ($M$) decreases with the increase in the formation factors; however, it increases with the increase in movable gas porosity, both showing a power function law. As shown in Figure 11bc, the pore structure index ($M$), which characterizes the microscopic pore structure parameters, is consistent with the experimental and theoretical values of the formation factor $F$ and movable gas porosity $\Phi_m$.

5.3. Influence of Microscopic Pore-Throat Structure Parameters on Relative Permeability. The characteristics of the maximum effective gas relative permeability based on the microscopic pore structure are shown in Figure 12. The maximum effective gas permeability of type I reservoirs is relatively large, and the range of movable gas porosity is relatively wide. The microscopic movable gas porosity had little effect on the maximum gas permeability. The maximum effective gas permeability of type II reservoirs was significantly lower than that of type I reservoirs, and the movable gas porosity was also concentrated in a relatively small range. Type III reservoirs have the lowest maximum effective gas permeability and a wide range of movable gas porosities. It can be seen that the maximum gas relative permeability value is not greatly affected by the microscopic pore-throat structure, such as movable porosity, and is mainly controlled by the comprehensive factors of the reservoir.

To study the correlation between the rock electrical properties and relative permeability under the influence of different micropore structures, we normalized and fitted the relative permeability curves of the three types of reservoirs. Combined with the theoretical model of the rock electrical properties, the change law of the relative permeability curve was analyzed.

5.4. Comparison of Electrical and Relative Permeability Experimental and Theoretical Results. Based on the Poiseuille formula and Darcy’s law, Ma et al.\textsuperscript{16} deduced a correlation model between the relative permeability and resistance increase coefficient. This model emphasizes the influence of bound water, which cannot flow in the medium but can conduct electricity. Liu et al.\textsuperscript{43} revised the relative permeability and resistance increase coefficient model proposed by Ma et al.\textsuperscript{16} (eq 13). The theoretical model in this study is based on the Liu modified model, combined with eq 9, to analyze and verify the experimental results of the relative permeability and resistance increase coefficient.

According to the model,

$$K_{rw} = \frac{1}{RI} \times \frac{(S_{w}^*)^3}{S_w}$$ \hspace{1cm} (13)

where $S_{w}^*$ is the normalized dimensionless water phase saturation, which can be calculated as follows

$$S_{w}^* = \frac{S_w - S_{wi}}{1 - S_{wi} - S_{w}}$$ \hspace{1cm} (14)

Combined with the Brooks–Corey formula, the calculation formula for the relative permeability of the gas phase according to eq 13 is as follows
The standardized values were obtained by normalization. The increase in permeability curves obtained according to the resistance permeability values. The normalized relative permeability curves permeabilities 

$$\begin{align*}
    K_{rw}^* &= K_{rw}/K_{rw}(S_w) \\
    K_{rg}^* &= K_{rg}/K_{rg}(S_w) \\
    K_{rw}^* &= c(S_w) d \\
    K_{rg}^* &= (1 - S_w^*)2(1 - S_w^{**})
\end{align*}$$

(15)

According to the definition of the gas—water standardized relative permeability, the relative permeability curve of the samples in the study area was standardized and normalized to obtain the average relative permeability curve. The standard results for the samples are listed in Table 2. The gas—water standardized relative permeability is defined as follows:

The characteristics of the three types of relative permeability curves are listed in Table 2. In the case of different normalized water saturations $S_w^*$, the normalized standard relative permeabilities $K_{rw}^*$ and $K_{rg}^*$ are calculated using eqs 16–19. The standardized values were obtained by normalization. The values of $K_{rw}$, $K_{rg}$ and $S_w$ were calculated from the relative permeability values. The normalized relative permeability curves obtained from the experiment were compared with the relative permeability curves obtained according to the resistance increase coefficient were compared and analyzed (Figure 13).

The relationship between the two-phase relative permeability curve and the water saturation obtained by standardizing the experimental data and deriving the electrical function theory is shown in Figure 13. According to the classification standard of the relative permeability curve obtained in the experiment, the normalized curve was divided into three types for comparative analysis. It can be seen from the comparison graphs of the three types of relative permeability curves that the standardized relative permeability curve obtained by the experiment is quite different from the relative permeability curve derived from the electrical function theory. The main reason for this difference is that the bound water in the pores cannot flow in two phases but can conduct electricity. The relative permeability curve derived from the theory of the electricity parameters of rock generally shifts to the left. The relative permeability curves of the water phase of the three types of reservoirs decreased, while the relative permeability curves of the gas phase showed little change; however, classification characteristics were not obvious. This shows that the electrical properties of rock have a significant influence on the relative permeability of the water phase but have little influence on the relative permeability of the gas phase.

A type I relative permeability curve diagram is shown in Figure 13a. The irreducible water saturation of the relative permeability curve was low, and the relative permeability of the gas phase in theory and experiment was higher than that of the water phase. The anhydrous gas production period was longer, and the on-site gas production was relatively high. The gas relative permeability curve of the theoretical model was higher than that of the experimental fitting; whereas the water relative permeability curve was lower than that of the experimental fitting. The water saturation corresponding to the isotonic point

| Table 2. Standardized Relative Permeability Curve Function Table in the Study Area |
|---------------------------|---------------------------|---------------------------|
| well | water permeability normalization function | gas-phase permeability normalization function | types |
| H1 | $K_{rw}^* = 0.0002(S_w^*)^{1.7879}$ | $K_{rg}^* = (1 - S_w^*)2(1 - S_w^{**})$ | II |
| H2 | $K_{rw}^* = 5 \times 10^{-6}(S_w^*)^{1.5366}$ | $K_{rg}^* = (1 - S_w^*)2(1 - S_w^{**})$ | III |
| H3 | $K_{rw}^* = 0.0006(S_w^*)^{1.3964}$ | $K_{rg}^* = (1 - S_w^*)2(1 - S_w^{**})$ | II |
| H4 | $K_{rw}^* = 3 \times 10^{-6}(S_w^*)^{1.1554}$ | $K_{rg}^* = (1 - S_w^*)2(1 - S_w^{**})$ | III |
| H5 | $K_{rw}^* = 6 \times 10^{-6}(S_w^*)^{0.9832}$ | $K_{rg}^* = (1 - S_w^*)2(1 - S_w^{**})$ | III |
| H6 | $K_{rw}^* = 0.0193(S_w^*)^{0.3104}$ | $K_{rg}^* = (1 - S_w^*)2(1 - S_w^{**})$ | I |
| H7 | $K_{rw}^* = 0.0208(S_w^*)^{0.2744}$ | $K_{rg}^* = (1 - S_w^*)2(1 - S_w^{**})$ | I |
| H8 | $K_{rw}^* = 3 \times 10^{-6}(S_w^*)^{0.0708}$ | $K_{rg}^* = (1 - S_w^*)2(1 - S_w^{**})$ | III |
| H9 | $K_{rw}^* = 0.0003(S_w^*)^{1.3444}$ | $K_{rg}^* = (1 - S_w^*)2(1 - S_w^{**})$ | II |
| H10 | $K_{rw}^* = 0.0018(S_w^*)^{0.1788}$ | $K_{rg}^* = (1 - S_w^*)2(1 - S_w^{**})$ | I |
| H11 | $K_{rw}^* = 0.0004(S_w^*)^{1.4664}$ | $K_{rg}^* = (1 - S_w^*)2(1 - S_w^{**})$ | III |
| H12 | $K_{rw}^* = 0.0673(S_w^*)^{0.262}$ | $K_{rg}^* = (1 - S_w^*)2(1 - S_w^{**})$ | I |

Figure 13. Normalized standard relative permeability curve experiment and theoretical curve fitting: (a) type I normalized relative permeability curve; (b) type II normalized relative permeability curve; and (c) type III normalized relative permeability curve.
increased, and the corresponding relative permeability decreased. Type II relative permeability curve diagram is shown in Figure 13b. The relative permeability curve of the gas phase derived based on the theory was higher than the experimental curve. The relative permeability curve of the water phase was lower than the experimental curve. The water saturation corresponding to the isotropic point increases. The experimental standard fitting results showed that the irreducible water saturation of this type of relative permeability curve was higher, and the irreducible water had a greater influence on the relative permeability of the two phases. The theoretical curve was similar to the experimental fitting curve, and both were concave. During the production of this type of gas well, irreducible water causes a larger drop in the theoretical water phase relative permeability curve compared with the experimental fitted curve. The type III relative permeability curve diagram is shown in Figure 13c. The experimental standard fitting results showed that this type of relative permeability curve has a higher irreducible water saturation. The relative permeability curve of the water phase was higher than that of the gas phase. The water content increases rapidly after the water breakthrough, and the gas production is low. In the theoretical derivation, the relative permeability curve of the gas phase increased significantly; however, the curve of the water phase almost coincided with the experimental fitting curve. This demonstrates that in the type III relative permeability curve, the electrical properties of the rock have a greater influence on the relative permeability of the gas phase.

In the actual gas reservoir development process, the two-phase seepage characteristics derived from the theory of the electrical properties of Type I are close to the actual two-phase flow characteristics. The relative permeability curve of the gas phase is steeper. The stage of gas recovery without water increased, and the water breakthrough time of the gas well well increased. The relative change in the water phase after the water breakthrough was close to the actual value. The type II theoretical derivation exhibited that the two-phase flow pattern was similar to the actual two-phase flow pattern. The relative permeability curve of the gas phase was steeper, and the relative permeability curve of the water phase was relatively flat. The water breakthrough time of the gas well was longer than the actual value. The gas well decreased rapidly after the water breakthrough. The moisture content increased slowly, and the theoretical stable production time was longer than the actual value. The relative flow characteristics of the type III curve gas changed significantly, which was far from the actual value. According to the theory of rock electrical properties, this type of gas reservoir has a higher gas recovery rate at the initial stage of exploitation. The stable production period was short, and the two-phase percolation zone was narrow. In the actual exploitation process, the single well production in the initial stage of this type of gas reservoir was low. There was almost no stage of anhydrous gas production when the two-phase core-permeability area was wide. After the water breakthrough, the water cut of this type of gas reservoir rises rapidly. Natural gas is difficult to produce, and only water is produced at the end of the gas well. This seepage characteristic can be clearly characterized from the relative permeability curves derived from the electrical theory and experimental fitting.

6. CONCLUSIONS

Based on the results of this study, the following conclusions can be drawn:

(1) A model of the relationship among electrical parameters, pore throat structure, and relative permeability of tight sandstone based on experimental data was established. The model presents typical three-terminal element characteristics. The porosity had a slight effect on the relative permeability. The significant effect of saturation index (n) on the relative permeability was also observed.

(2) Theoretical and experimental models represented the relationship among pore structure characterization, rock electrical parameters, and relative permeability. The electrical parameters of the sample were greatly affected by the microscopic pore structure. The theoretical value was closely related to the experimental data. The maximum gas relative permeability was less affected by the microscopic pore structure, such as movable porosity, but was controlled by the comprehensive factors of the reservoir.

(3) The theoretical model of the relative permeability derived from the electrical parameters is quite different from the experimental model. The reason for the difference is that irreducible water could not flow but conduct electricity. Therefore, the isotonic point saturation of the phase permeability curve derived from the rock element theory was greater than that obtained from the experiment.

(4) The relative permeability curves of the three types of theoretical and experimental models were compared. The theoretical and experimental fitting curves had similar concave shapes. The relative permeability curve of the theoretical model gas phase was higher than the experimental fitting curve; however, the relative permeability curve of the water phase was lower than the experimental fitting curve. This shows that the irreducible water makes the theoretical gas-phase relative permeability amplitude higher than the experimental fitting curve. In the theoretical derivation, the influence of the irreducible water should be corrected.

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Notes
The authors declare no competing financial interest.

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