Academic Journal of Science and Technology
ISSN: 2771-3032 | Vol. 12, No. 2, 2024

Review on the Study of Microscopic Pore Structure and Seepage Characteristics

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Abstract: Pore structure, as the focus of researchers, is also one of the main contents of reservoir geological research, and the characteristics of percolation depend on the micro-pore structure of the reservoir. The study of the characteristics of fluid percolation in the reservoir plays an important role in formulating a reasonable oil and gas exploitation scheme. Understanding the micro pore structure of the reservoir, analyzing the pore throat structure inside the oil and gas reservoir, and systematically studying the micro seepage characteristics of the reservoir have far-reaching influence and great significance for the exploration and development of oil and gas fields.

Keywords: Pore Structure; Pore Throat Structure; Seepage Characteristics; Oil and Gas Exploration.

1. Introduction

Micro-pore structure and seepage characteristics are the core contents of oil and gas reservoir research [1]. The research on the micro-pore structure of reservoir rocks covers the spatial scale, shape, size, distribution characteristics of pores and the degree of connectivity between pores, which can reflect the effective reservoir space of the whole reservoir [2]. Oil, gas and water flow in the pores connected by the reservoir rocks, and the pore structure characteristics have an important influence on the fluid flow in the pores. Therefore, the study of the pore structure characteristics of the rock is the basis of the study of the fluid flow law. With the rapid development of science and technology, experimental instruments and research methods have been gradually improved and perfected. The study of microscopic pore structure has changed from the qualitative study in the initial stage to the quantitative characterization at the current stage, and the application conditions of various test means have been deeply understood by scholars. At present, domestic and foreign scholars have made a lot of contributions to the micro-pore structure of reservoirs.

Percolation refers to the flow of fluid in porous medium. Rock is a naturally formed porous medium material, and there are a large number of irregular and multi-scale microscopic pores in it, which determine the seepage characteristics of fluid. Therefore, studying the seepage characteristics of fluid in reservoir plays an important role in formulating a reasonable oil and gas exploitation plan [3]. The research results on the characteristics of micro-seepage in reservoirs are mainly reflected in two aspects: first, the breakthrough in the theoretical direction of micro-seepage mechanism such as starting pressure gradient, high-speed non-Darcy seepage, slippage limit, stress sensitivity, wettability, water film thickness, and pore throat radius; The second is to focus on the updating of experimental methods and technologies such as cast thin slice, scanning electron microscope, mercury injection test, nuclear magnetic resonance test, phase permeability curve test, microscopic water and oil displacement experiment and three-dimensional CT scanning [3-20]. Pore structure is the material basis of oil and gas migration and preservation in formation, and is the first step to study reservoir properties. After determining the spatial properties of oil and gas, the seepage characteristics of fluid are the research focus of further oil and gas exploitation.

2. Research Status of Microscopic Pore Structure Characteristics

With the improvement of oil and gas exploration level, the research methods of reservoir micro-pore structure are constantly improving. The research method has also changed from the early simple physical property parameter analysis method to the present advanced scientific and technological means to analyze the micro pore structure of the reservoir. In terms of experimental means: early qualitative and semi-quantitative static description simple analysis (thin slice microscopy, scanning electron microscopy, image pore method) → early 20th century conventional mercury injection capillary curve method → At the end of the 20th century, constant rate mercury injection, nuclear magnetic technology and other semi-quantitative and quantitative study of reservoir micro-pore structure characteristics. In terms of theoretical research, it mainly includes physical model and fractal model, among which the real microscopic sandstone model is the most widely used [21-27].

2.1. Research Methods of Pore Structure

2.1.1. Casting Sheet

The thin sheet of the cast body is a thin sheet of rock that is injected with colored liquid glue under vacuum pressure into the pore space of the rock and ground after the liquid glue is solidified. Because the pores of the rock are filled with colored glue, it is very eye-catching and easy to identify under the microscope. The cast thin slice experiment can make statistics on the matching relationship between pores, the number of throats and the pore throats in the thin slice. At present, the cast thin slice is one of the more simple, accurate and widely used methods for qualitative identification of pores and throats. Besides the characterization of pore throats, it is also important for the identification of various diagenetic minerals and the evidence of diagenetic evolution [28-31]. However, the cast thin slice can only reflect the pore throat characteristics on the two-dimensional plane, and the size, shape and distribution of some pores (intergranular pores, etc.) cannot be truly reflected. Zhao Ming et al. [32] proved that the reservoir property and seepage capacity could be evaluated under microscopic conditions by using cast thin sections. Liu Qingli et al. [33] obtained reservoir porosity by using cast thin slice image analysis. Liu Ye et al. [34] constructed the feature space of rock classification by extracting feature parameters from the original color of the cast thin slice image and its morphological gradient.

2.1.2. Scanning Electron Microscopy

Scanning electron microscopy (SEM) is the use of very fine-focused high-energy electron beam scanning on the rock sample, stimulate a variety of physical information, through the acceptance of these information, magnification and display imaging, to obtain the surface topography of the test sample. The appearance of scanning electron microscopy makes up for the shortage of cast thin sheets, which can effectively identify the distribution of reservoir pore throat in three-dimensional space, and accurately characterize pore size, morphology and other related parameters. At the same time, it can use energy spectrum analysis to qualitatively analyze the minerals that cannot be identified. Environmental scanning electron microscopy can be used to directly analyze water-containing oil samples under low vacuum conditions and environmental conditions, which can better reflect the original state of the samples, and also can study the shape and structure of solid substances in the liquid, effectively reflecting the microscopic characteristics of the reservoir. Hu Yuanyuan [35] et al. used scanning electron microscopy to demonstrate the morphology and occurrence of clay minerals in the reservoir. Wang Baofeng [36] et al. introduced the application of environmental electron microscopy in petroleum technology. Liu Weixin et al. [37] used environmental scanning electron microscopy to directly analyze water-containing oil samples under low vacuum conditions and environmental conditions, which could better reflect the original state of the samples, and also study the form and structure of solid substances in the liquid, effectively reflecting the microscopic characteristics of the reservoir. Yu Liang et al. [38] observed the morphology and distribution characteristics of clay minerals in the reservoir and the degree of their influence on the pore structure (porosity and permeability) of the reservoir through scanning electron microscopy.

2.1.3. High-pressure Mercury Injection

High-pressure mercury injection technology is one of the most commonly used technical means to study the structural characteristics of microscopic pore throat. Its principle is that during the injection process, the injection pressure is continuously increased so that the non-wetting phase mercury (mercury) can overcome the capillary resistance between the pores of the rock and be injected into the pores of the rock sample. When the pressure value is stable, the pressure value and the amount of mercury injected are recorded. According to Washburn equation, the corresponding pore distribution and pore volume under different pressures can be calculated, and the capillary pressure curve can be obtained. The shape of the capillary pressure curve can reflect the micro-pore characteristics of the reservoir from multiple angles, so as to better evaluate the micro-pore throat characteristics of the reservoir. By analyzing the shape characteristics and related parameters of mercury injection curve, characteristics such as reservoir pore throat size, distribution, sorting and connectivity can be studied [39-43]. High-pressure mercury injection technology has a large mercury inlet pressure, the maximum mercury inlet pressure can reach 400MPa at present, and the pore throat radius of 1.8nm or above can be detected. It is one of the effective means to characterize the pore throat size distribution of unconventional oil and gas reservoirs on a large scale, and it is widely used in the study of tight sandstone, tight carbonate and shale. According to the characteristics of capillary pressure curve, the pore size, sorting coefficient, distortion, maximum pore radius, mercury removal efficiency and other parameters can be calculated, and the pore structure of the reservoir can be qualitatively and quantitatively characterized, and the oil recovery can be estimated combined with the field data. Gongyanjie et al. [44] obtained the lower limit of flow gap in tight oil reservoirs through high-pressure mercury injection technology. Wang Xin [45] et al obtained the distribution of medium and large pores in shale pores by using the high-pressure mercury injection curve. Pittman ED[46] et al. analyzed the relationship between various parameters in the capillary force curve of sandstone reservoirs and the porosity and permeability. Wang Ruifei [47] et al. defined mercury withdrawal saturation parameters by using high-pressure mercury injection technology. Zhang Wenda et al. [48] used capillary pressure line morphology as a standard to classify pore structure types. Sun Lijuan et al. [49] used the capillary force curve to deduce the pore structure parameters of sandstone. He Chengzu [50] et al studied the quantitative relationship between pore structure and physical properties of low permeability sandstone gas reservoirs based on the capillary bundle model.

2.1.4. Constant Velocity Mercury Injection

Constant rate mercury injection and high pressure mercury injection have the same principle, the difference is that constant rate mercury injection is a very low constant speed (usually 5×10-5mL/min), can ensure the occurrence of quasi static mercury injection process, with quasi static mercury injection process into the rock pores, in this process, the interfacial tension and contact Angle remain unchanged. Every pore shape change at the mercury inlet end will cause the shape of the meniscus to change. First, mercury preferentially enters the large pore in the sample. When the pore is filled with mercury, mercury will enter the next connected pore through the throat, and then the pressure drop will occur, resulting in the change of the capillary pressure of the system. The pores and throats inside rocks can be separated by detecting the pressure rise and fall during mercury injection. The capillary pressure curves of pores and throats can be provided by the test results of constant velocity mercury injection. Pore radius, throat radius, pore throat radius ratio and other rock microscopic pore throat structure characteristic parameters can be calculated according to the pressure. Gao Yongli et al. [51] used constant velocity mercury injection test to quantitatively evaluate the difference of micro-pore throat structure in low permeability reservoirs, and believed that the size and distribution of throat affected the final development effect. Feng Yongjun et al. [52] studied the influence of pore and throat on capillary curve based on in-depth analysis of constant velocity mercury injection. Zhang Wenkai et al. [53] effectively characterized the total pore throat size of the sandstone of Xiaoheba Formation by using experiments such as constant velocity mercury injection, and believed that the sandstone permeability was mainly controlled by a small part of thicker pore throat. Wang Jing et al. [54] discussed the size and distribution characteristics of pores and throats and their relationship with permeability based on the constant velocity mercury injection experiment.

The results showed that shale samples with different permeability showed similar pore size distribution characteristics but greatly different throats distribution characteristics.

2.1.5. CT scan

Computed tomography (CT) technology, referred to as CT technology, is a high-resolution microscopic image processing technology [55]. Ct scan can reconstruct three-dimensional stereoscopic model with high resolution and obtain spatial pore throat distribution morphology, distribution scale, connectivity and physical properties parameters, which can more accurately and quantitatively characterize microscopic pore structure. Zhiming [56] et al. used CT scanning technology to characterize the microscopic pore structure, fracture distribution and microscopic fluid characteristics of the reservoir from a three-dimensional perspective. Kristianl[57] et al studied the characteristics of water-driven oil by using CT tomography images. Shi, B.Z[58] et al analyzed the fracture development of shale reservoir by using CT imaging technology. Bai Bin et al. [59] used CT scanning technology to comprehensively characterize the pore throat structure characteristics of tight sandstone reservoirs. Ma,T.SI[60] et al. studied the microscopic characteristics of shale reservoirs based on CT scanning technology. Using CT technology, Guan Xin [61] et al., taking the anthracite sample from Xinjing mining area, Yangquan Mining area, Qinshui Basin as an example, carried out fine characterization and three-dimensional reconstruction analysis of pore structure and connectivity of high coal grade coal. Li Aifeng et al. [62] used CT technology to scan cores in different steam flooding stages, build three-dimensional digital core models, extract pore network models, and obtain core porosity, absolute permeability, pore structure related characteristics and other parameters in different steam flooding stages.

2.1.6. Nuclear Magnetic Resonance

Nuclear magnetic resonance (NMR) is used to evaluate the pore structure of rocks by studying the nuclear magnetic properties of pore fluids and their vibration properties under the action of applied magnetic field. The signal measured by NMR is superimposed by the signal of hydrogen atoms in pores of different sizes, and the NMR T2 distribution is obtained through complex mathematical fitting, so the T2 distribution reflects the distribution of rock pore size.

Yang Zhengming [63] et al. used nuclear magnetic resonance technology to study the mobile fluid saturation of samples of different lithologies in volcanic gas reservoirs, and obtained the lower limit of centrifugal force and throat radius corresponding to the mobile fluid. Timur,A[64] et al studied the parameters of mobile fluid saturation, porosity and permeability of sandstone reservoirs by using nuclear magnetic resonance technology in 1969. Freeman et al. [65] used nuclear magnetic resonance logging to characterize fluid characteristics. Mai et al. [66] used low-field nuclear magnetic resonance to determine the porosity distribution in carbonate reservoirs. Li Haibo et al. [67] converted the distribution of pore radius by nuclear magnetic resonance T-spectrum. Talabi,O[68] et al used nuclear magnetic resonance technology to respond to aperture simulation. Wang Zhenhua [69] et al believe that the permeability predicted by NMR has a large deviation from the conventional permeability results. Gao,H[70] et al. measured the mobile fluid saturation and mobile fluid porosity of ultra-low permeability reservoirs using nuclear magnetic resonance technology. Zheng Ke et al. [71] used nuclear magnetic resonance technology to evaluate mobile fluids in three different lithologic low permeability reservoirs in China. Hofman JP [72], Yun Huayun [73], Liu Tangyan [74] and others successively converted T2 spectral curve into nuclear magnetic capillary force curve, and then some scholars and others improved the previous construction method [75-77]. Li Aifen et al. [78] converted T2 spectrum distribution into pore throat distribution and evaluated pore structure characteristics of tight oil reservoirs.

3. Research Status of Seepage Characteristics

The study of reservoir seepage characteristics has a reliable theoretical basis for the formulation of late oilfield development plan and the improvement of oil recovery. In recent years, with the continuous deepening of the study of low permeability reservoir, the study of low permeability reservoir seepage characteristics has made more progress. At present, studies on seepage characteristics mainly include theoretical studies on seepage mechanism, interpenetration experiments and nuclear magnetic resonance experiments based on digital characterization, as well as glass-filled sand models, microsimulation lithography models and real sandstone models that visually describe the seepage process and residual oil distribution [79-82]. All these methods are the research methods summarized by researchers in the process of exploration, and have made great contributions to the study of micro-seepage characteristics of reservoirs.

3.1. Relative Permeability Experiment

The relative permeability and saturation curve of fluid is the basis for studying the flow of fluid in porous media. The curve can reflect the basic characteristics of the flow capacity and interaction degree of oil, water, gas and water, and is an important theoretical basis for studying the formation, evaluation and development of oil and gas reservoirs. At present, there are two kinds of obtaining of the phase permeability curve. One is the steady state method, which is determined according to Darcy's law formula and relative permeability definition formula under steady state flow. Another unsteady state law determines the seepage difficulty of different fluids in rock samples according to the dynamic change of injected water. Unsteady state method is a commonly used test method because of its simple and short measurement time and the flow capacity of multiphase fluids under the conditions of actual oil and gas reservoirs [83-84]. In addition, with the deepening of research, some scholars have proposed some new methods to determine oil-water phase permeability. Jiang Kailiang [85] proposed a method suitable for steady-state and unsteady experiments of oil-water phase permeability in low permeability reservoirs by deducing the unsteady state of oil-water phase permeability in low permeability reservoirs and the calculation formula of the steady-state method. Zhang Xingxing [86] obtained a method to eliminate the influence of dead pore volume by analyzing the influence of pore volume that does not participate in seepage flow on oil-water phase permeability curve, and proposed a method to correct oil-water relative permeability curve by using the principle of the relationship between water saturation and resistivity. Zhang Fengzhu [87] deeply studied the characteristics of oil-water phase permeability in low permeability reservoirs and obtained the oil-water phase permeability curve suitable for low permeability reservoirs. Through the research of many scholars, it is found that the difference between the characteristics of the phase permeability curve of low permeability reservoir and conventional reservoir mainly lies in the relative permeability of oil and water at the isotonic point. The relative permeability at the isotonic point of low permeability reservoir is generally lower than 0.1, and the phase permeability curve is significantly affected by the capillary force, and the isotonic point is tilted to the left. In addition, the characteristics of the phase permeability curve are also affected by the micro-pore throat structure of the reservoir, the wettability of the rock surface, and the fluid flow velocity [88-89].

3.2. Visualization of Seepage Characteristics

The characteristics of fluid flow in the reservoir cannot be observed directly through the analysis of experimental parameters such as relative permeability and nuclear magnetic resonance. In recent years, through the continuous exploration of domestic and foreign experts, a major breakthrough has been made, and a physical model that can be used to observe the characteristics of oil-water seepage through a microscope has been proposed to realize the visualization and quantification of the water-driven oil process [90-92]. At present, the successful visualization models mainly include glass sand filling model, microsimulation lithography model and real sandstone model.

Glass sand filling model is the use of glass sand microbeads (particle diameter of 0.125 ~ 0.2mm), pore diameter of about 0.05 ~ 0.08mm, as a porous medium placed between the glass plate, the surrounding with glue seal. Zhu Jiucheng [93] used the glass-filled sand model to conduct water displacement oil experiments under different viscosity ratios and displacement velocities, and proposed methods to confirm the conditions limiting displacement velocities and parameters such as water displacement displacement. The micro-etching model is made of the actual pore network engraved on the glass plate by laser etching. The size and shape of the pore throat are similar to the actual pore throat shape of the reservoir. Shi Zhanzhong et al. [94] studied the distribution and formation mechanism of remaining oil by using the microscopic lithography simulation model. The results show that the method of water displacement, reservoir heterogeneity and Jamin effect are the main reasons for the formation of residual oil. The remaining oil mainly has a continuous distribution pattern of medium to large pore and medium to coarse pore throat. Local continuous distribution pattern of residual oil in small to medium pore and medium pore throat type and dispersed residual oil in fine pore throat type. The real sandstone model is a sandstone model made by slicing, grinding, fixing and sealing the real core on the glass sheet according to a certain size. This model retains all the physical and chemical properties of the core, and the flow process of fluid in it is closer to the flow state in the reservoir, and the results obtained are widely recognized [95-98]. Qu Zhihao [99] used the real sandstone model to explore the low permeability reservoir, simulated the reservoir formation process and water drive development process of oil entering the reservoir, and discussed the characteristics of water drive seepage and residual oil during the experiment. The results show that there are two types of water oil displacement in pores: non-piston and piston displacement. The piston displacement type has better oil displacement effect. After non-piston displacement, there are more residual oil and various types of residual oil, mainly in residual reservoirs such as cluster residual oil formed by flow around, spot residual oil formed by oil droplet sticking off, and thick oil film formed by uneven flow rate in pores. Zhu Yushuang et al. [100-101] analyzed the influence of water sensitivity on seepage characteristics in waterflood development by using real sandstone models, and conducted series and parallel studies on the influence of heterogeneity in the models.

3.3. Study on Seepage Mechanism

3.3.1. Starting Pressure Gradient

The complex pore throat structure and the physical properties of the skeleton particle surface of low permeability sandstone reservoir make its seepage characteristics different from conventional reservoirs. The main manifestation is that the pore throat of the reservoir is small, and the effect of pore wall on fluid seepage is great, showing the phenomenon of non-Darcy seepage. In the process of reservoir development, there is a general starting pressure gradient in low permeability reservoirs [102-106]. For the real starting pressure gradient test, the "pressure difference-flow" method is usually adopted at present, and the seepage velocity inside the core is recorded under different displacement pressure differences, while the pseudo starting pressure gradient parameter is obtained by calculating the relationship between the flow rate and the pressure gradient using the quadratic function method, and then applying the mathematical formula to obtain the parameter. Dong Dapeng et al. [107] were the first to conduct well test studies considering starting pressure gradient for low permeability homogeneous and dual media reservoirs. Deng Yinger et al. [108] studied the seepage mechanism of starting pressure gradient at low speed, and concluded that the increasing amplitude of starting pressure gradient was relatively obvious in reservoirs with low permeability. Huang Yanzhang et al. [109] obtained three kinds of non-Darcy seepage equations at low speed by experimental method and evaluated them. Yao Yudong et al. [110] conducted dimensionless analysis on the experimental data of core seepage, and divided the seepage process into three sections: ultra-low speed, low speed and Darcy seepage zone. Tan Leijun et al. [111] obtained the starting pressure gradient by using both stable and unstable well testing methods.

The mechanism of nonlinear seepage is relatively complex, and domestic and foreign scholars have carried out a lot of research work on it. In summary, the main factors of nonlinear seepage are as follows: (1) The characteristics of porous media. The porosity and permeability of ultra-low permeability reservoir are reduced due to the deformation of rock skeleton due to the small throat and the change of pressure during production. Complex physical and chemical changes occur between injected fluid and rocks and minerals, causing clay expansion and mineral particle migration, which results in the change of fluid flow law. (2) rheological properties of fluid. Petroleum is a complex system composed of different components and components with different properties, which has the properties of non-Newtonian fluids. (3) liquid-solid action. Due to the polarity of molecules at the solid-liquid interface, a boundary layer adsorbed on the pore wall cannot participate in the flow, resulting in nonlinearity.

3.3.2. Study on Slippage Effect

For gas seepage, there is a "slippage effect" at low pressure. The collision between gas molecules and pore walls is the physical mechanism of slippage, which is determined by the structure of the pore medium and the distribution of the free path of gas molecules. The slippage phenomenon will cause the deviation of the gas seepage law from the Darcy line in the low pressure section. The denser the pores and the lower the gas pressure, the more obvious the deviation caused by this phenomenon. In terms of theoretical application research on slippage effect, Turgay Ertekin et al considered the influence of slippage factor on seepage flow during the calculation of seepage concentration field and disaster field of multi-component gas. A large number of Chinese scholars have studied slippage effect and established corresponding gas reservoir engineering methods and numerical simulation methods considering slippage effect [112-115].

3.3.3. Stress Sensitivity Study

Geertsma first defined rock volume compression coefficient and pore compression coefficient to quantitatively represent pore volume changes caused by changes in reservoir pore pressure [116]. Hall calculated the relationship between pore compression coefficient and porosity through a large number of experiments [117]. A large number of experiments show that stress variation has a great influence on the permeability of low permeability reservoir, and the more cracks and the smaller the permeability of bedrock, the greater the influence. However, the effect on porosity is small, and the change of porosity with stress is not considered under normal circumstances. Many other experts and scholars at home and abroad have also studied the impact of effective stress on reservoir physical properties. In summary, there are two ways to consider the impact of stress on permeability: one is to describe the permeability variation modulus, and the other is to describe the coupling between stress field and seepage field through complex fluid-solid coupling.

4. Summary

Pore structure, as the focus of researchers, is also one of the main contents of reservoir geological research, and the characteristics of seepage depends on the micro pore structure of the reservoir. Clarifying the micro pore structure of the reservoir, analyzing the pore throat structure inside the oil and gas reservoir, and conducting systematic and comprehensive research on the micro seepage characteristics of the reservoir have far-reaching influence and great significance for the exploration and development of oil and gas fields. With the development and progress of research technology, the analysis and testing methods of reservoir micro-pore structure and its seepage characteristics have also undergone fundamental changes, from simple physical property analysis to advanced experimental testing, and its research theories show the cross-disciplinary characteristics of geology, chemistry, mathematics and physics. At present, the research on micro-pore structure of low permeability (ultra-low permeability) reservoir shows a development direction from qualitative description to quantitative characterization and two-dimensional to three-dimensional, and the proportion of pore structure simulation and fractal direction in theoretical basic research tends to increase. All these technological changes and theoretical innovations not only promote the development of fine quantitative characterization of micro-pore structure of low permeability (ultra-low permeability) reservoirs, but also enrich its accurate guidance for the later development of low permeability (ultra-low permeability) reservoirs. At present, there are many methods to study fluid distribution in rock pore system, but the correlation is weak. Static analysis of cast thin slice, scanning electron microscopy (SEM) and X-ray diffraction, dynamic study of high pressure mercury injection, constant velocity mercury injection, nuclear magnetic resonance (NMR) and microscopic water flooding can be carried out. Different experimental testing methods only describe the flow law and distribution characteristics of fluid from a single experimental perspective. However, the study on the distribution law and characteristics of remaining oil has certain reference value and guiding significance, while other computational fluid distribution methods belong to relatively macroscopic computer simulation technology, and do not introduce the influence parameters of microscopic seepage mechanism and microscopic characteristics factors, so the field production practice guidance is weak, especially in the high water cut reservoir in the late stage of development. How to combine the micro research results with the macro calculation will be a development direction of oil and gas field development research.

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