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Characterization and Evaluation of Reservoir Micro-Pore Structure in Unconventional Oil and Gas Reservoir Development

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Abstract

Unconventional oil and gas reservoirs have the typical characteristics of "low porosity, low permeability and strong heterogeneity", and their microscopic pore structure is the core factor to control the occurrence, migration and development efficiency of oil and gas. This paper systematically summarizes the technical system and theoretical method of characterization and evaluation of reservoir micro-pore structure. It is pointed out that at present, there are challenges such as difficulty in multi-scale data fusion, insufficient data heterogeneity and model adaptability, and interference of mineral composition, and the data difference between different technologies can reach more than 30%. The future development direction lies in the development of "macro-micro-nano" multi-scale technology chain, the integration of artificial intelligence algorithms to achieve seamless data connection, the promotion of four-dimensional dynamic monitoring technology, the establishment of standardized evaluation models, and the expansion to cross-cutting fields such as CO_2 storage, and the construction of a "high-precision-full-scale-dynamic" comprehensive characterization system, which provides theoretical support for the efficient development of unconventional oil and gas.

Keywords

Oil and Gas Reservoir Development; Reservoir; Micro-Pore Structure; Characterization and Evaluation.

1. Introduction

The reservoir characteristics of unconventional oil and gas reservoirs are significantly different from those of traditional conventional reservoirs, and its core characteristics are "low porosity, low permeability and strong heterogeneity". For example, the pore diameter in shale gas reservoirs is usually between 30 and 200 nanometers, and the permeability of tight sandstone is generally lower than 0.1 millidarcy (mD). The complexity of this microscopic pore structure directly leads to the difficulty in accurately describing and predicting oil and gas occurrence, migration mechanism and development efficiency through traditional theories and methods.

Micro-pore structure, as the "genetic code" of unconventional reservoirs, is the core element to control the process of oil and gas occurrence, adsorption, desorption, diffusion and seepage [1]. On one hand, the morphology, size, connectivity, and surface properties of pores determine the occurrence form and distribution patterns of oil and gas within reservoirs. On the other hand, the complexity of the pore network directly influences the propagation path of hydraulic fracturing fractures, the filtration characteristics of fracturing fluids, and the stimulated reservoir volume (SRV), ultimately determining well productivity and development economics [2]. Therefore, accurate characterization and scientific evaluation of reservoir micro-pore structure are the theoretical basis and technical premise for revealing unconventional oil and gas enrichment law, optimizing development plan and improving oil recovery. This paper aims to systematically sort out the technical system and theoretical methods of characterization and evaluation of micro-pore structure of unconventional oil and gas reservoirs, analyze the shortcomings and challenges of existing research, and put forward the future development direction of multi-technology integration, dynamic simulation and standardized evaluation, so as to provide theoretical support and technical reference for efficient development of unconventional oil and gas.

2. Micro-pore Structure Characterization Technology System

2.1. Principles of Technical System Construction

1) Full scale coverage. It covers micro-scale to nano-scale pores (usually < 2 nm is micropore, 2–50 nm is mesopore and > 50 nm is macropore), and realizes continuous characterization from macro to micro.
2) Multi-method fusion. Combining qualitative and quantitative means, the advantages of different testing principles complement each other to improve the characterization accuracy.
3) Structure-function association. It not only describes the pore geometry, but also relates its influence on reservoir, permeability, adsorption and other functional properties.
4) Dynamic evolution perspective. Considering the dynamic influence of diagenesis, organic matter evolution and fracturing transformation on pore structure.

2.2. Composition of Technical System

In the development of unconventional oil and gas reservoirs, the characterization and evaluation of reservoir micro-pore structure is the key to reveal reservoir characteristics, optimize development plan and improve oil recovery. With the development of nano-materials science, physical chemistry and analytical chemistry, the micro-pore structure characterization technology has made remarkable progress, forming a multi-dimensional technical system covering direct observation, indirect measurement and numerical simulation [3].

1. Direct observation technology

Two-dimensional field emission scanning electron microscope directly observes the morphology, size and connectivity of pores through high-resolution imaging, which is suitable for qualitative analysis of micro-to nano-scale pores [4]. Micro-nano CT scanning combined with three-dimensional reconstruction technology can realize three-dimensional visualization of pore structure, and can quantitatively analyze pore throat distribution, connectivity and complex network characteristics [5].

2. Indirect determination technique

Gas adsorption methods such as N_2/CO_2 adsorption analyze pore size distribution through adsorption isotherms, where N_2 adsorption is suitable for mesopores (2-50 nm) and CO_2 adsorption is targeted for micropores (<2 nm). Fractal theory is often introduced to quantify pore heterogeneity [6]. Mercury injection method and nuclear magnetic resonance method determine the radius distribution of pore throat by injecting mercury solution, while the latter inverts pore structure based on fluid relaxation time, which is especially suitable for low permeability and tight reservoirs.

3. Numerical simulation technology

Digital core simulation combined with CT images establishes a mathematical model to simulate fluid migration process and predict permeability and productivity. Molecular dynamics simulation explores the mechanism of gas adsorption/desorption in pores and helps optimize displacement efficiency [7].

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2.3. Frontier Development Direction

Full-scale joint characterization integrates multi-technical data, and realizes full aperture coverage from nanometer to millimeter level through algorithm splicing, thus solving the problem of scale limitation of single method. AI and four-dimensional imaging use AI algorithm to improve the efficiency of image processing, and dynamically monitor the evolution of pore structure in combination with time dimension (4D) to reduce the calculation cost [8]. Cross-domain application expansion extends characterization technology to supercritical carbon dioxide storage, underground hydrogen storage and other fields, and explores the influence of pore structure on carbon storage efficiency and hydrogen storage safety.

3. Evaluation Parameter System of Reservoir Micro-Pore Structure

Micro-pore structure of reservoir is the core factor to control the occurrence and seepage of unconventional oil and gas (shale gas, tight oil gas and coalbed methane), and its complexity (low porosity, low permeability, strong heterogeneity and multi-scale pore network) requires the establishment of a systematic evaluation parameter system. The system needs to cover multi-dimensional parameters such as pore geometry, connectivity, heterogeneity and fluid occurrence state, and provide basis for reservoir classification, dessert optimization and development scheme optimization.

3.1. Porosity and Permeability-The Core Indexes of Reservoir Storage and Seepage Capacity

Table 1. Key parameters and test methods of porosity and permeability

Parameters	Definition	Test Methods	Typical Range for Unconventional Reservoirs	Significance
Total Porosity	Total pore volume fraction in rock	Helium method, density method	2%–8% (shale); 4%–15% (tight sandstone)	Total reservoir volume
Effective Porosity	Connected pore volume fraction	Mercury compression method (related to mercury expulsion efficiency)	1%–6% (shale); 2%–10% (tight sandstone)	Reservoir fluid storage capacity
Permeability	Reciprocal of fluid flow resistance	Mercury compression method ($K = (r^2 \Delta P)/(8\mu L)$), pulse attenuation method	<0.1 mD (shale); 0.1–1 mD (tight oil)	Fluid flow resistance

Porosity (Φ) and permeability (K) are fundamental parameters for describing the storage capacity and fluid flow capacity of a reservoir. However, in unconventional reservoirs, both are significantly affected by the microscopic pore structure, and need to be further understood through microscopic scale characterization (as shown in Table 1).

Porosity refers to the ratio of pore volume to total volume in rocks, which reflects the total amount of reservoir space. The porosity of unconventional reservoirs is generally less than 10% (mostly 2%~8%), and nano-scale pores are dominant (pore size < 100 nm). Porosity can be divided into total porosity (including invalid porosity) and effective porosity (connected porosity), in which effective porosity directly determines movable fluid reserves [9].

Permeability represents the seepage ability of fluid in porous media, and the unit is mD (millidarcy). Unconventional reservoirs have extremely low permeability (often less than 0.1 mD), which belongs to the category of ultra-low permeability-nanometer seepage. Permeability is controlled by pore structure (especially pore throat radius and tortuosity), and can be indirectly calculated by mercury injection experiment (capillary pressure curve obtained by high-pressure mercury injection), gas adsorption (specific surface area measured by BET method) or nuclear magnetic resonance (NMR).

3.2. Heterogeneity Evaluation - Spatial Heterogeneity Characterization of Micro Pore Structure

Unconventional reservoirs are highly heterogeneous (from nano to micron pores coexist), which directly affects fluid distribution and seepage path. The evaluation of heterogeneity should pay attention to pore size distribution, pore throat connectivity and spatial distribution (see Table 2). Using scanning electron microscopy (SEM) and focused ion beam-scanning electron microscopy (FIB-SEM), one can identify various pore types including organic pores (formed by organic matter hydrocarbonization), inorganic pores (interstitial mineral pores, dissolution pores), and microfractures, while also quantifying pore size distributions. Organic pores can constitute 30% to 70% of shale pore volume, with pore sizes predominantly concentrated between 5 and 200 nm [10]. Pore-throat coordination number (the number of throats connected by a single pore), throat radius (controlling capillary force) and pore-throat ratio (the ratio of pore diameter to throat diameter) are the key parameters. For example, the smaller the throat radius, the greater the capillary force and the higher the irreducible water saturation; The larger the pore-throat ratio, the greater the fluid flow resistance [11]. Quantify the spatial variation in pore network anisotropy, development of bedding fractures (natural microfracture density), and organic matter abundance (TOC) through CT scanning (micron-nano CT) or thin section analysis.

Table 2. Key parameters and significance of heterogeneity evaluation

Parameter Category	Specific Parameters	Definition/Test Methods	Significance
Pore Size Distribution	Average Pore Size, Pore Size Distribution Coefficient	SEM/FIB-SEM image analysis, gas adsorption (BJH model)	Reflects the uniformity of pore size and the dominant flow pathways
Pore Throat Connectivity	Pore Throat Coordination Number, Median Throat Radius	Mercury porosimetry capillary pressure curve (threshold pressure, median pressure)	Controls the complexity of fluid seepage routes
Spatial Heterogeneity	Anisotropy Index, TOC Planar Variation Coefficient	CT scan 3D reconstruction, thin section statistical analysis	Evaluates the continuity of sweet spots and development difficulty

3.3. Evaluation of Fluid Occurrence State-Dynamic Equilibrium between Adsorption and Free Phase

The fluid (oil, gas and water) in unconventional reservoirs has complex occurrence states, including adsorption state (molecular force attached to solid surface), free state (filled in pores) and dissolved state (dissolved in kerogen or asphaltene). The evaluation focuses on the ratio of adsorbed gas/oil to free gas/oil, which is very important for resource calculation.

As shown in Table 3, the Langmuir model was used to determine the Langmuir volume (VL, the maximum adsorption capacity) and the Langmuir pressure (PL, the pressure when the adsorption capacity reaches half). The adsorption capacity of shale gas is usually 1 ~ 5 m/t (standard state), which is controlled by the type of organic matter (the type I kerogen has the strongest adsorption capacity), maturity (the highest when Ro=1.0%~2.0%) and pore specific surface area (BET specific surface area) [12].

The T2 spectrum (transverse relaxation time) measured by nuclear magnetic resonance (NMR) is used to distinguish fluids in pores with different pore sizes (short T2 corresponds to bound water/adsorbed gas in small pores and long T2 corresponds to free gas/oil in large pores). In addition, mercury injection method can estimate the saturation of movable fluid by mercury withdrawal efficiency. The ratio of adsorbed amount to free amount is controlled by reservoir pressure (when the pressure decreases, the adsorbed gas is desorbed and converted into free gas). For example, in shale gas reservoirs, when the reservoir pressure is higher than the bubble point pressure, free gas is dominant; Below the bubble point pressure, the contribution ratio of adsorbed gas increases [13].

Table 3. Key parameters and methods for evaluation of fluid occurrence state

Parameters	Definition	Test Methods	Significance
Langmuir Volume (VL)	Maximum adsorption capacity per unit mass of rock	Methane Isothermal Adsorption Experiment (Langmuir Model)	Assessing the potential of adsorbed gas resources
Langmuir Pressure (PL)	Pressure at which adsorption reaches VL/2	Same as above	Predicting the critical pressure for desorption of adsorbed gas
Free Gas Saturation	Volume fraction of free natural gas	NMR T2 Spectrum, Core Gas Content Testing	Reflecting the scale of mobile fluids
BET Specific Surface Area	Total surface area per unit mass of rock	Low-Temperature Nitrogen Adsorption (BET Model)	Positive correlation with adsorbed gas capacity (greater specific surface area yields higher adsorption capacity)

4. Technical Challenges and Development Direction

4.1. Existing Challenges

Although the existing technologies, such as field emission scanning electron microscope and micro-nano CT, can achieve nano-scale resolution, the high resolution leads to a narrow field of view, which is difficult to reflect the macro-heterogeneity of reservoirs. Gas adsorption method (N_2/CO_2) is suitable for micro-mesoporous analysis, mercury injection method covers macro-pores but may destroy pore structure, while CT scanning can be reconstructed in three dimensions but is limited by resolution and calculation cost [14]. How to combine and standardize multi-source data is still a difficult problem. There are often data contradictions between indirect measurement technology and direct observation technology. For example, the difference between the pore throat radius distribution measured by high-pressure mercury injection and the CT three-dimensional model can reach more than 30%, so it is urgent to establish a unified correction model.The diversity of mineral composition in tight reservoirs leads to the increase of the error of fractal dimension calculation model. Experiments show that the systematic deviation of CO_2adsorption method in fractal calculation of micropore section is 15% ~ 20% [15].

4.2. Future Trend

Develop "macro-micro-nano" multi-scale technology chain, combine low-field nuclear magnetic resonance (millimeter level), micro-nano CT (micron-nano level) and gas adsorption (sub-nano level), and realize seamless data connection through machine learning algorithm. For example, AI is used to optimize CT image segmentation and fractal parameter extraction to improve the prediction accuracy of porous media connectivity. Four-dimensional imaging technology (3D+ time dimension) is developed to monitor the evolution of pore structure in the process of hydraulic fracturing in real time. Synchrotron radiation X-ray tomography has realized the dynamic observation of in-situ fluid displacement experiment of core, and it is necessary to reduce the dependence of equipment in the future to promote it to industrial application. A deep learning framework is introduced to process massive microscopic images, automatically identify pore types and quantify fractal dimensions. Combining geostatistics with seepage mechanics, a permeability prediction model based on fractal theory is constructed to solve the coupling problem of low permeability reservoir parameters [16]. Explore the pore response mechanism in the process of exploiting shale gas by supercritical CO_2displacement method, and reduce the environmental risk of hydraulic fracturing. At the same time, develop low-cost alternative technologies, such as environmental protection drilling fluid and low-frequency electromagnetic imaging, to balance the characterization accuracy and economic benefits.

In a word, the current unconventional reservoir characterization faces core challenges such as multi-scale fragmentation, heterogeneous data and insufficient model adaptability. In the future, it is necessary to build a comprehensive characterization system of "high precision-full scale-dynamic" through technology integration innovation and intelligent algorithm empowerment, so as to provide theoretical support for efficient development of unconventional oil and gas.

5. Conclusion

The nonlinear coupling relationship between porosity and permeability, the cooperative control mechanism of pore throat coordination number and tortuosity, and the composite occurrence mode of organic pores and inorganic pores significantly affect the adsorption and desorption characteristics and flow efficiency of shale gas/tight oil. Aiming at the existing technical bottleneck, a multi-scale technology chain of "macro-micro-nano" is developed and combined with machine learning algorithm to realize cross-scale data fusion. Develop four-dimensional imaging technology to monitor the pore evolution in the process of fracturing and reconstruction in real time; A permeability prediction model based on fractal theory is constructed to solve the coupling problem of low permeability reservoir parameters. This achievement provides theoretical support and technical path for the efficient development of unconventional oil and gas, especially lays a scientific foundation for the optimization of dessert area, the optimization of hydraulic fracturing scheme and the improvement of carbon storage efficiency, and marks the paradigm shift of microscopic pore structure characterization from single parameter analysis to multi-physical field coupling simulation.

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