

Advances and Challenges in the Characterization of Micro-pore Structures in Tight Sandstone Reservoirs for Unconventional Oil and Gas Exploration

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Abstract

Tight sandstone oil and gas exploration represents one of the pivotal areas in the field of unconventional hydrocarbon resources. The characterization of micro-pore structures within these reservoirs is crucial for understanding the seepage mechanisms and mastering the enrichment patterns of oil and gas. With the evolving focus of micro-pore structure research, significant advancements have been made in recent years in the development of characterization techniques for tight sandstone reservoirs. This paper reviews the progress in two major stages: (1) qualitative-semi-quantitative research, which emphasizes micro-fractures, reservoir properties, wettability, sensitivity, water flooding and oil-water relative permeability, pore and throat types, sizes, and distributions, primarily utilizing scanning electron microscopy (SEM), thin section observation, X-ray diffraction (XRD), and conventional mercury injection capillary pressure (MICP) tests; and (2) semi-quantitative-quantitative research, which shifts towards the quantitative characterization of pore and throat planar distributions, cement types, and cementation styles, employing techniques such as environmental SEM, nuclear magnetic resonance (NMR), constant-rate mercury injection, and digital core characterization based on two-dimensional SEM images and three-dimensional computed tomography (CT) scans. Despite these advancements, three primary challenges remain: (1) balancing the precision and scale in the characterization of pore structures in tight sandstone reservoirs; (2) achieving breakthroughs in the combined characterization of full-pore-size distribution; and (3) enhancing the integration of digital core technology with artificial intelligence (AI). Looking ahead, the characterization of micro-pore structures in tight sandstone reservoirs should prioritize the following aspects: (1) investigating the dynamic variations of pore-throat structures in response to decreasing fluid pressure during reservoir development, with a focus on the gradual contraction of fine and complex pore-throat systems; and (2) exploring methods to enhance oil recovery by lowering the threshold of movable throat radii, based on the control of pore-throat structures over seepage capacity and hydrocarbon mobilization in tight reservoirs.

Keywords

Tight Sandstone Reservoirs; Micro-pore Structure Characterization; Unconventional Oil and Gas; Digital Core Technology; Artificial Intelligence.

1. Introduction

The global energy landscape is undergoing a profound transformation, with unconventional oil and gas resources playing an increasingly significant role in meeting global energy demands[1]. Among

these resources, tight sandstone oil and gas has emerged as a key focus due to its vast potential and strategic importance[2]. Unlike conventional reservoirs, tight sandstone formations are characterized by low permeability and porosity, posing significant challenges in exploration, development, and production. Understanding the micro-pore structures within these reservoirs is paramount for unraveling their seepage mechanisms and optimizing production strategies[3,4].

This paper aims to provide a comprehensive review of the advancements and challenges in the characterization of micro-pore structures in tight sandstone reservoirs. We begin by outlining the significance of this research area and the evolving focus of micro-pore structure studies. Subsequently, we delve into the two major stages of research development, discussing the methodologies employed and the insights gained. Finally, we identify the remaining challenges and propose future research directions to further advance the field.

2. Significance of Micro-pore Structure Characterization in Tight Sandstone Reservoirs

Micro-pore structures in tight sandstone reservoirs are critical for determining the fluid storage and flow properties of these formations. The complex interplay between pores, throats, and cementation can significantly influence the permeability, porosity, and hydrocarbon saturation of the reservoir. Therefore, a thorough understanding of these micro-structures is essential for predicting reservoir performance, optimizing production strategies, and maximizing hydrocarbon recovery.

In recent years, with the increasing focus on unconventional oil and gas resources, the characterization of micro-pore structures in tight sandstone reservoirs has become a research hotspot. Advances in technology and methodologies have enabled more detailed and accurate investigations into these micro-structures, providing valuable insights into the seepage mechanisms and hydrocarbon enrichment patterns in tight sandstone formations.

3. Evolution of Micro-pore Structure Research Focus

The evolution of micro-pore structure research in tight sandstone reservoirs can be broadly divided into two stages: qualitative-semi-quantitative research and semi-quantitative-quantitative research.

3.1 Qualitative-Semi-quantitative Research Stage

During this stage, research efforts were primarily focused on identifying and describing the basic characteristics of micro-pore structures in tight sandstone reservoirs. This included the identification of micro-fractures, the evaluation of reservoir properties such as permeability and porosity, and the investigation of wettability, sensitivity, and water flooding behavior. Additionally, researchers paid attention to the types, sizes, and distributions of pores and throats within the reservoir.

To achieve these objectives, a variety of methodologies were employed, including scanning electron microscopy (SEM), thin section observation, X-ray diffraction (XRD), and conventional mercury injection capillary pressure (MICP) tests. SEM provided high-resolution images of pore and throat structures, allowing for the identification of different pore types and the assessment of pore connectivity. Thin section observation, on the other hand, enabled the evaluation of reservoir properties and the investigation of cementation styles. XRD was used to analyze the mineralogical composition of the reservoir rocks, while MICP tests provided quantitative information on pore size distributions.

3.2 Semi-quantitative-Quantitative Research Stage

As research progressed, the focus shifted towards more quantitative investigations of micro-pore structures in tight sandstone reservoirs[5]. This stage saw the development of advanced characterization techniques that enabled the quantitative assessment of pore and throat planar distributions, cement types, and cementation styles.

Environmental SEM, nuclear magnetic resonance (NMR), and constant-rate mercury injection were among the key techniques employed during this stage. Environmental SEM provided images of pore and throat structures under controlled environmental conditions, allowing for a more accurate assessment of pore connectivity and throat sizes. NMR, on the other hand, offered a non-destructive method for measuring pore size distributions and fluid saturation levels. Constant-rate mercury injection provided more detailed information on pore throat size distributions and connectivity compared to conventional MICP tests.

In addition to these techniques, digital core characterization based on two-dimensional SEM images and three-dimensional CT scans emerged as a powerful tool for the quantitative assessment of micro-pore structures in tight sandstone reservoirs. By reconstructing three-dimensional models of reservoir rocks, digital core characterization enabled the visualization and quantification of pore and throat structures at unprecedented resolutions.

4. Advancements in Micro-pore Structure Characterization Techniques

The rapid development of characterization techniques has significantly advanced our understanding of micro-pore structures in tight sandstone reservoirs. In this section, we review the key advancements made in both qualitative-semi-quantitative and semi-quantitative-quantitative research stages.

4.1 Qualitative-Semi-quantitative Research Techniques

4.1.1 Scanning Electron Microscopy (SEM)

SEM has been widely used in the characterization of micro-pore structures in tight sandstone reservoirs. By providing high-resolution images of pore and throat structures, SEM allows for the identification of different pore types, the assessment of pore connectivity, and the measurement of pore sizes.

Recent advancements in SEM technology have further enhanced its capabilities for micro-pore structure characterization. For instance, the development of field emission guns (FEGs) and backscattered electron detectors (BSEs) has improved the resolution and contrast of SEM images, enabling a more accurate assessment of pore and throat structures.

4.1.2 Thin Section Observation

Thin section observation is a traditional method for evaluating reservoir properties and investigating cementation styles in tight sandstone formations. By examining thin slices of reservoir rocks under a microscope, researchers can assess the mineralogical composition, porosity, and permeability of the rocks.

Advancements in thin section preparation techniques and microscopy have improved the quality and resolution of thin section images. This, in turn, has enabled a more detailed and accurate assessment of reservoir properties and cementation styles in tight sandstone reservoirs.

4.1.3 X-ray Diffraction (XRD)

XRD is a powerful tool for analyzing the mineralogical composition of reservoir rocks. By measuring the diffraction patterns of X-rays scattered by the rock sample, researchers can identify the different minerals present in the rock and determine their relative abundances.

Recent advancements in XRD technology, such as the development of high-resolution diffractometers and the use of synchrotron radiation sources, have further improved the accuracy and resolution of mineralogical analyses. This has enabled a more detailed understanding of the mineralogical composition and texture of tight sandstone formations.

4.1.4 Conventional Mercury Injection Capillary Pressure (MICP) Tests

MICP tests are a widely used method for measuring pore size distributions in reservoir rocks[6]. By injecting mercury into the rock sample under controlled pressure conditions, researchers can determine the size distribution of pores and throats within the rock.

Recent advancements in MICP technology have focused on improving the accuracy and resolution of pore size measurements. For instance, the development of high-pressure MICP systems has enabled the measurement of pore sizes down to the nanometer scale. Additionally, the use of automated data acquisition and analysis software has streamlined the data processing workflow and reduced the potential for human error.

4.2 Semi-quantitative-Quantitative Research Techniques

4.2.1 Environmental Scanning Electron Microscopy (ESEM)

ESEM is a variant of SEM that allows for the imaging of samples under controlled environmental conditions. This capability enables the visualization of pore and throat structures in tight sandstone formations that are otherwise difficult to observe due to their small sizes and complex geometries.

Recent advancements in ESEM technology have focused on improving the resolution and contrast of images, as well as enhancing the ability to control environmental conditions during imaging. These advancements have further enhanced the capabilities of ESEM for the characterization of micro-pore structures in tight sandstone reservoirs.

4.2.2 Nuclear Magnetic Resonance (NMR)

NMR is a non-destructive method for measuring pore size distributions and fluid saturation levels in reservoir rocks. By applying a magnetic field to the rock sample and measuring the relaxation times of the hydrogen nuclei within the fluid-filled pores, researchers can determine the size distribution of pores and the fluid saturation levels within the rock.

Recent advancements in NMR technology have focused on improving the sensitivity and resolution of measurements, as well as developing new methodologies for data analysis and interpretation. These advancements have enabled a more detailed and accurate assessment of pore size distributions and fluid saturation levels in tight sandstone formations.

4.2.3 Constant-rate Mercury Injection

Constant-rate mercury injection is a variant of MICP tests that provides more detailed information on pore throat size distributions and connectivity compared to conventional MICP tests. By injecting mercury into the rock sample at a constant rate, researchers can measure the pressure required to fill different-sized pores and throats, thereby obtaining a more detailed picture of the pore throat size distribution within the rock.

Recent advancements in constant-rate mercury injection technology have focused on improving the accuracy and resolution of measurements, as well as developing new methodologies for data analysis and interpretation. These advancements have enabled a more detailed and accurate assessment of pore throat size distributions and connectivity in tight sandstone formations.

4.2.4 Digital Core Characterization

Digital core characterization is a powerful tool for the quantitative assessment of micro-pore structures in tight sandstone reservoirs. By reconstructing three-dimensional models of reservoir rocks based on two-dimensional SEM images or three-dimensional CT scans, researchers can visualize and quantify pore and throat structures at unprecedented resolutions.

Recent advancements in digital core characterization technology have focused on improving the accuracy and resolution of three-dimensional models, as well as developing new methodologies for data analysis and interpretation. These advancements have enabled a more detailed and accurate assessment of micro-pore structures in tight sandstone formations, providing valuable insights into their seepage mechanisms and hydrocarbon enrichment patterns.

5. Remaining Challenges in Micro-pore Structure Characterization

Despite the significant advancements made in the characterization of micro-pore structures in tight sandstone reservoirs, several challenges remain. In this section, we identify three primary challenges and discuss their implications for future research.

5.1 Balancing Precision and Scale in Pore Structure Characterization

One of the primary challenges in micro-pore structure characterization is balancing the precision and scale of pore structure measurements. While high-resolution techniques such as SEM and ESEM provide detailed information on pore and throat structures at the microscale, they are often limited in their ability to capture the full range of pore sizes present in tight sandstone formations. Conversely, techniques such as MICP and NMR can measure pore size distributions over a broader range of scales but may lack the precision required for a detailed understanding of micro-pore structures.

Addressing this challenge requires the development of new methodologies that can capture the full range of pore sizes present in tight sandstone formations while maintaining the precision required for a detailed understanding of micro-pore structures.

5.2 Achieving Breakthroughs in Full-pore-size Distribution Characterization

Another challenge in micro-pore structure characterization is achieving breakthroughs in the combined characterization of full-pore-size distributions. Current techniques are often limited in their ability to measure pore sizes across the entire range from nanometers to micrometers, which is critical for a comprehensive understanding of seepage mechanisms and hydrocarbon enrichment patterns in tight sandstone formations.

Addressing this challenge requires the development of new methodologies that can accurately measure pore sizes across the entire range from nanometers to micrometers. This may involve the integration of multiple techniques or the development of entirely new approaches for pore size measurement.

5.3 Enhancing the Integration of Digital Core Technology with Artificial Intelligence (AI)

Finally, another challenge in micro-pore structure characterization is enhancing the integration of digital core technology with AI[7]. While digital core technology provides powerful tools for the quantitative assessment of micro-pore structures, the analysis and interpretation of the vast amounts of data generated by these techniques can be time-consuming and labor-intensive.

The integration of AI with digital core technology has the potential to streamline this process by automating data analysis and interpretation tasks. However, significant challenges remain in terms of the development of accurate and reliable AI algorithms, as well as their integration with existing digital core technology platforms.

6. Future Research Directions

To address the challenges identified above and further advance the field of micro-pore structure characterization in tight sandstone reservoirs, we propose the following future research directions:

6.1 Investigating Dynamic Variations of Pore-throat Structures under Changing Fluid Pressure Conditions

One promising research direction is to investigate the dynamic variations of pore-throat structures in tight sandstone formations under changing fluid pressure conditions. As fluid pressure decreases during reservoir development, pore-throat structures may undergo significant changes, such as the gradual contraction of fine and complex pore-throat systems.

Understanding these dynamic variations is critical for predicting reservoir performance and optimizing production strategies. Future research should focus on developing new methodologies for measuring pore-throat structures under changing fluid pressure conditions and investigating the mechanisms responsible for their dynamic variations.

6.2 Exploring Methods to Enhance Oil Recovery by Lowering the Threshold of Movable Throat Radii

Another promising research direction is to explore methods for enhancing oil recovery in tight sandstone formations by lowering the threshold of movable throat radii. The movable throat radius is

a critical parameter that determines the seepage capacity and hydrocarbon mobilization potential of tight sandstone formations.

By lowering the threshold of movable throat radii, researchers may be able to unlock additional hydrocarbon reserves that were previously inaccessible due to their small pore sizes and complex geometries. Future research should focus on developing new methodologies for measuring movable throat radii and investigating the factors that influence their sizes and distributions within tight sandstone formations.

6.3 Enhancing the Integration of Digital Core Technology with AI

Finally, another important research direction is to enhance the integration of digital core technology with AI. By leveraging the power of AI, researchers can automate data analysis and interpretation tasks, thereby streamlining the workflow and reducing the potential for human error.

Future research should focus on developing accurate and reliable AI algorithms for the analysis and interpretation of digital core data, as well as integrating these algorithms with existing digital core technology platforms. Additionally, researchers should explore the potential of AI for predicting reservoir performance and optimizing production strategies based on the insights gained from digital core data.

7. Conclusion

The characterization of micro-pore structures in tight sandstone reservoirs is critical for understanding their seepage mechanisms and mastering the enrichment patterns of oil and gas. Significant advancements have been made in recent years in the development of characterization techniques for these formations, enabling a more detailed and accurate assessment of their pore and throat structures.

Despite these advancements, several challenges remain, including balancing precision and scale in pore structure characterization, achieving breakthroughs in full-pore-size distribution characterization, and enhancing the integration of digital core technology with AI. To address these challenges and further advance the field, future research should focus on investigating dynamic variations of pore-throat structures under changing fluid pressure conditions, exploring methods for enhancing oil recovery by lowering the threshold of movable throat radii, and enhancing the integration of digital core technology with AI.

By continuing to push the boundaries of micro-pore structure characterization in tight sandstone reservoirs, researchers can contribute to the sustainable development of unconventional oil and gas resources and help meet the growing global energy demands.

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