Experimental Study on the Thermal Response Characteristics of Porosity in Sandstone

Yuan Gao, Jianxin Bai, Zhengchuan Zhu, Xingxing Wang, Dong Huang, Jian Jiao

Yan'an Checun Coal Industry (Group) Co., Ltd., Yan'an City, Shaanxi Province, 716000, China

Abstract

The pore structure of sandstone directly influences its physical and mechanical properties as well as its fluid seepage capacity, with temperature being a key factor in altering this structure. This study simulates thermal effects by heating sandstone samples in a muffle furnace to explore the evolution patterns of sandstone porosity under different temperatures. Standard sandstone samples were primarily selected, prepared, and then heated isothermally at various temperatures. Porosity was measured based on the physical process where non-wetting liquid, driven by pressure, overcomes surface tension to infiltrate pores. This research provides crucial experimental evidence for understanding the damage mechanisms in sandstone reservoirs under thermal stress and offers guiding significance for engineering practices such as oil-type gas management.

Keywords

Sandstone; Heat Treatment; Porosity; Thermal Damage; Temperature Effect; Muffle Furnace.

1. Introduction

Sandstone is a type of sedimentary rock formed by the cementation of mineral grains such as quartz through a cementing agent. Due to its typically high porosity, sandstone serves as an important aquifer and hydrocarbon reservoir. High temperatures can alter the microstructure of sandstone, leading to significant changes in its physical and mechanical properties. Among these properties, porosity, as a core parameter characterizing reservoir and seepage capacities, is particularly crucial in understanding its thermal evolution patterns. As an experimental apparatus capable of providing a uniform and controllable high-temperature environment, a muffle furnace is an effective means for studying the thermal damage behavior of rocks [1].

Scholars both domestically and internationally have extensively investigated the impact of temperature on sandstone porosity and achieved notable results [2-4]. However, there are three main deficiencies in existing research: First, some studies focus on a single temperature point or a limited temperature range, lacking in-depth exploration of the dynamic evolution patterns of porosity under continuous temperature conditions. Second, there is a lack of comprehensive examination of the coupling relationships between sandstone's mineral composition, microstructure, and porosity, failing to fully reveal the intrinsic connections between mineral phase transitions, micro-crack propagation, and porosity changes under temperature effects. Third, significant variations in experimental conditions and methods limit the comparability of results, making it difficult to form a unified theoretical model [5]. In response to these deficiencies, this paper aims to conduct systematic experiments to thoroughly analyze the change patterns and underlying mechanisms of sandstone porosity during the heating process in a muffle furnace.

Currently, although some studies have focused on the thermal effects on macroscopic parameters such as sandstone strength and wave velocity, there is still a need for deeper quantitative and systematic research on porosity, a fundamental physical property parameter, across different temperature ranges. Therefore, this study focuses on sandstone and aims to reveal the change patterns of its porosity under different temperature levels through meticulously designed muffle furnace heating experiments. By analyzing the underlying physical and chemical mechanisms, this research seeks to provide theoretical support and data references for thermal safety evaluations and optimizations in relevant engineering fields.

2. Sampling Process

2.1. Source of Sandstone Samples

The rock samples for this study were collected from the auxiliary transportation roadway on the west wing of Lucun No.2 Coal Mine, the No.101 return air roadway of Lucun No.2 Coal Mine, and the No.102 auxiliary transportation roadway of Lucun No.1 Coal Mine. To ensure the representativeness and homogeneity of the samples, sampling locations were chosen to avoid obvious fractures and weathered zones. Professional coring equipment was used to obtain core samples, and water cooling was employed during the drilling process to minimize thermal disturbance and mechanical damage to the rock samples. The extracted cores were immediately wrapped in tin foil, labeled with stratigraphic horizons and orientations, placed in dedicated core boxes, and transported to the laboratory.

The primary reason for selecting sandstone from these locations as the research object is the occurrence of crude oil seepage in these areas. The mineral composition of the sandstone mainly includes quartz, feldspar, and small amounts of mica and clay minerals [6]. Quartz grains, with their high hardness and chemical stability, serve as the main framework component of the sandstone. Feldspar grains, to a certain extent, influence the mechanical properties and chemical reactivity of the sandstone. This mineral composition enables thermal expansion differences among the minerals to induce internal stress changes when the sandstone is subjected to temperature effects, thereby impacting the pore structure. In terms of structure, the sandstone features moderately sized grains, medium sorting, good roundness, predominantly point-contact between grains, and mainly muddy cementation. These structural characteristics determine the initial porosity and pore connectivity of the sandstone, providing a favorable basis for studying the changes in porosity under temperature effects [7]. Therefore, investigating the changes in porosity of this sandstone under high-temperature conditions holds significant practical importance for ensuring safe coal mine operations.

2.2. Sample Processing

In the laboratory, the rock cores were cut into cylindrical specimens with a height of approximately 100 mm. All specimens underwent end-face grinding to ensure that both ends were flat, smooth, and had a parallelism error of less than 0.05 mm. After preparation, the specimens were numbered, cleaned, and then placed in a constant-temperature oven at 105°C for 48 hours to reach a constant weight, thereby thoroughly removing free water and some adsorbed water from the pores. The dried specimens were then placed in a desiccator to cool to room temperature (25°C) for subsequent use. Ultimately, a total of 20 standard specimens were prepared and randomly divided into six groups, corresponding to six target temperature points (room temperature, 200°C, 400°C, 600°C, 800°C, and 1000°C) to ensure the statistical reliability of the experimental results.

3. Experimental Process

3.1. Experimental Equipment and Materials

The primary equipment used in this experiment was an SX_2-4-10A box-type muffle furnace manufactured by Shaoxing Shangyu Daoxu Kexi Instrument Factory, as shown in Figure 1. This muffle furnace is capable of reaching a maximum operating temperature of 1000°C, with a rated power of 4 kW and a furnace chamber size of 300 mm × 200 mm × 120 mm. It features rapid heating rates and high temperature control accuracy, with a temperature control precision of ±1°C. The furnace employs an intelligent PID control system, enabling precise control over the heating process. The heating elements are composed of molybdenum disilicide rods, which exhibit excellent high-temperature resistance and stability, allowing for prolonged and stable operation in high-temperature environments. The furnace chamber is lined with high-quality ceramic fiber material, which possesses extremely low thermal conductivity and excellent thermal insulation properties. This effectively minimizes heat loss, enhances energy efficiency, and reduces the surface temperature of the furnace, thereby ensuring the safety of experimental operations.

Figure 1. SX$_2$-4-10A Box-type Muffle Furnace

The porosity measuring instrument selected is the Anton Paar PM20-PoroWin, Version 8.11 mercury intrusion porosimetry analyzer, as shown in Figure 2. Based on the physical process where a non-wetting liquid, driven by pressure, overcomes surface tension to intrude into pores, this instrument can accurately measure parameters such as the porosity, specific surface area, pore volume, and pore size of materials. It offers high testing accuracy, with a repeatability error of less than ±2%, and an extremely wide pore size measurement range (typically 0.003–1000 μm), covering nearly the entire spectrum from micropores to macropores.

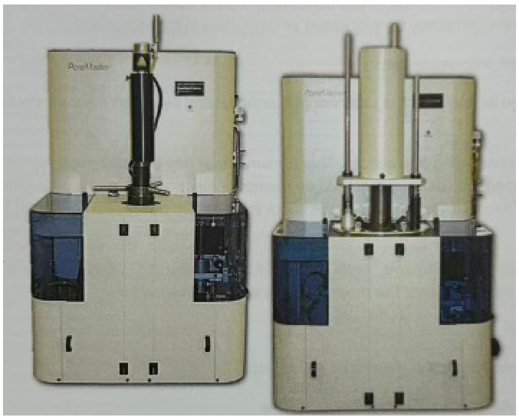

Figure 2. Mercury Intrusion Porosimetry Analyzer

3.2. Experimental Scheme Design

This experiment aims to comprehensively investigate the variation patterns of porosity in sandstone under different temperature and heating time conditions. In terms of temperature settings, considering the temperature ranges that sandstone may encounter during natural geological processes and engineering applications, as well as the maximum operating temperature of the muffle furnace, six temperature gradients were established, ranging from room temperature (25°C) to 1000°C. These gradients are 25°C, 200°C, 400°C, 600°C, 800°C, and 1000°C, respectively.

Regarding the determination of heating time, relevant research literature and preliminary experimental results were referenced to set the holding time at each temperature point to 4 hours. This is because, in preliminary experiments, it was observed that when the holding time was less than 4 hours, the internal temperature distribution of the sandstone samples was uneven, preventing them from reaching a fully thermal equilibrium state, which resulted in significant fluctuations in the porosity measurement results. Conversely, when the holding time exceeded 4 hours, the trend of porosity changes tended to stabilize, and further extending the holding time had a minimal impact on the experimental results. Therefore, selecting 4 hours as the holding time ensures that the samples reach thermal equilibrium at the given temperature while improving experimental efficiency.

3.3. Experimental Operational Procedures

First, place the processed sandstone samples into a drying oven and dry them to a constant weight at 105°C to remove moisture from the samples. Accurately weigh the mass of the dried samples using an electronic balance, recording it as m_1. Measure the diameter (d) and height (h) of the samples with a vernier caliper, and calculate the initial volume of the samples as $V_1 = \pi(d/2)^2h$. Carefully place the weighed and measured samples into the muffle furnace and close the furnace door. Set the heating program of the muffle furnace to gradually increase the temperature from room temperature to the predetermined experimental temperature at a rate of 5°C/min.

Once the muffle furnace reaches the predetermined temperature, start timing and maintain the temperature constant for 4 hours. During the holding period, closely monitor the temperature display of the muffle furnace to ensure that temperature fluctuations remain within ±1°C, thereby ensuring the stability of the experimental conditions. After the holding period ends, turn off the power supply of the muffle furnace and allow the samples to cool naturally to room temperature within the furnace. Natural cooling prevents the generation of excessive thermal stresses inside the samples due to rapid cooling, which could otherwise affect the microstructure and porosity of the samples [8-9].

After cooling, remove the samples from the muffle furnace and weigh them again using an electronic balance, recording the mass as m_2. Inspect the samples for any visible cracks, fractures, or other damage and document the observations. Place the samples into the porosity measuring instrument and conduct porosity tests according to the instrument's operational manual. Prior to testing, calibrate and adjust the porosity measuring instrument to ensure its accuracy and stability. During testing, strictly control the temperature and humidity of the testing environment to avoid interference from external factors with the test results. After testing, read and record the porosity data of the samples from the instrument as n_1.

Follow the above procedures to sequentially heat, cool, and test the porosity of the three samples at each temperature point, recording all experimental data. Throughout the experimental process, strictly adhere to laboratory safety protocols to ensure experimental safety. After each experiment, clean and maintain the experimental equipment to prepare for the next experiment.

Figure 3. Comparison between Rock Heated to 1000°C and Untreated Rock

4. Experimental Results

4.1. Porosity Data of Sandstone Under Different Heating Conditions

Through rigorous experimental operations and precise data measurements, detailed porosity data for sandstone under various heating conditions were obtained, as specifically shown in Table 1. From Table 1, it can be observed that the porosity of sandstone exhibits a distinct trend of change under different heating temperatures. As the temperature increases, the porosity of the sandstone gradually rises.

Table 1. Porosity of Rock Samples at Different Temperatures

Temperature/°C	Porosity of Sample 1/%	Porosity of Sample 2/%	Porosity of Sample 3/%
25	15.1950	15.3253	15.0329
200	15.3889	15.6233	15.5237
400	19.2936	19.6587	19.0326
600	22.5216	22.3216	22.7325
800	25.8565	25.4498	25.5235
1000	27.0994	28.1235	28.3256

4.2. Trends in Porosity Variation with Heating Parameters

Within the temperature range from room temperature to 200°C, the increase in porosity is relatively slow, with a small curve slope, indicating that temperature has a relatively weak impact on porosity. This is because, at lower temperatures, the thermal expansion effect of mineral particles within the sandstone is not significant, and the relative displacement between particles is minor. The changes in pore structure are primarily due to the evaporation of moisture and the decomposition of a small amount of weakly bound minerals, leading to a certain degree of increase in porosity, albeit with a limited magnitude.

Once the temperature exceeds 200°C, the rate of porosity increase significantly accelerates, with a larger curve slope. Between 200°C and 800°C, some minerals in the sandstone undergo phase transformations, such as the dehydration and decomposition of clay minerals and the decomposition of calcite. These phase transformation reactions cause changes in mineral volume, generating new pores and microcracks, which rapidly increase porosity. Meanwhile, as the temperature rises, the thermal expansion differences between mineral particles gradually increase, intensifying thermal stress effects and further promoting the expansion and interconnection of microcracks, which also contributes to the increase in porosity.

In the high-temperature range of 800°C to 1000°C, porosity continues to rise. At this stage, mineral phase transformations in the sandstone become more intense, with extensive mineral decomposition and recrystallization, further complicating the pore structure and significantly increasing both the number and size of pores. Additionally, thermal stress concentration within the rock becomes more severe at high temperatures, leading to the development of macroscopic cracks within the rock. These macroscopic cracks interconnect with microscopic pores and microcracks, greatly increasing the porosity of the sandstone.

The porosity of sandstone gradually increases. When the heating time is relatively short, the rate of porosity increase is rapid. However, as the heating time is further extended, the rate of porosity increase gradually slows down. This is because, during the initial heating phase, heat transfer and physicochemical reactions within the rock occur rapidly. Mineral decomposition, phase transformations, and thermal stress effects lead to the rapid formation and expansion of pores, resulting in a rapid increase in porosity. As heating time continues, reactions within the rock gradually reach equilibrium, and the rate of new pore formation and expansion slows down, consequently reducing the rate of porosity increase.

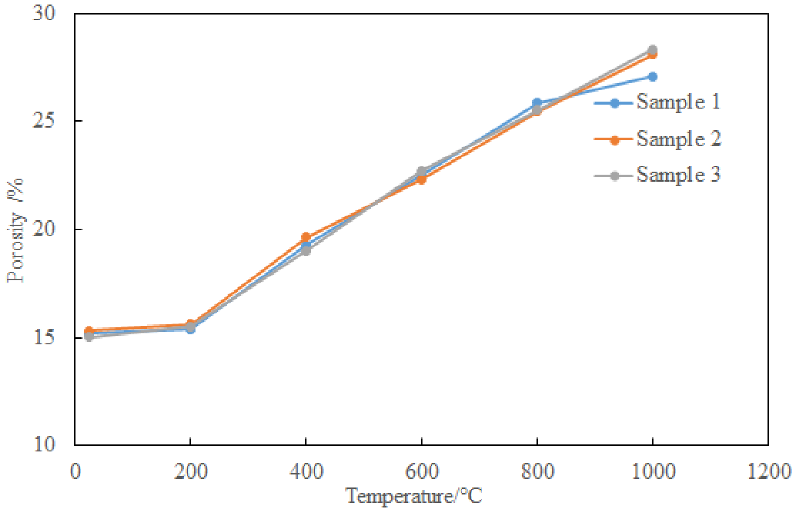

Figure 4. Variation of Porosity with Temperature

5. Results Analysis and Discussion

5.1. Mechanisms of Heating on Sandstone Porosity

Heating affects sandstone porosity primarily through three mechanisms: First, thermal expansion. The differences in thermal expansion coefficients among various minerals generate uneven thermal stresses. When these stresses exceed the cementation strength, microcracks form. During the low-temperature phase, these microcracks expand with increasing temperature and time, thereby increasing pore volume. Second, mineral phase transformations. Clay minerals undergo dehydration and decomposition at different temperatures, while carbonate minerals decompose at high temperatures, releasing gases that escape and generate micropores and cracks, altering the microstructure. Third, changes in cementing materials. Siliceous, calcareous, and argillaceous cements undergo melting and recrystallization, dissolution and decomposition, as well as dehydration, shrinkage, and decomposition at different temperatures, respectively. This decline in cementing ability results in rock loosening and an increase in porosity [10].

5.2. Comparison with Relevant Research Findings

Consistency: The porosity of sandstone increases with temperature, with a slower rate at low temperatures and a faster rate at high temperatures. The temperature at which porosity rapidly increases is lower than the temperature at which thermal expansion forces sharply intensify, which aligns with the research conducted by Chen Lunjian et al. Below 150°C, the filling of medium to large pores results in slow porosity growth, while above 600°C, the generation of numerous new pores corresponds to the permeability changes studied by Zhao Yiqing et al., validating the experimental rationale [11-12]. Differences also exist: In some studies, the magnitude of porosity increase in sandstone over specific temperature ranges differs from that in this study. This discrepancy stems from variations in the source of sandstone samples (initial mineral composition, microstructure, cementation type), experimental conditions (heating rate, holding time), and testing methods.

5.3. Interactive Effects of Influencing Factors

Interaction between heating temperature and time: An increase in temperature accelerates the rate of porosity increase. At low temperatures (200°C), short-term heating (1 hour) results in minimal porosity changes due to moisture evaporation and slight mineral thermal expansion. Extending the heating time to 4 hours allows thermal stress to accumulate, significantly increasing porosity. At high temperatures (600°C), short-term heating triggers significant mineral phase transformations, rapidly increasing porosity. Although porosity continues to rise with prolonged heating, the growth rate slows down as internal physicochemical reactions approach equilibrium.

Interaction between initial properties and temperature/time: Sandstone rich in clay minerals is more significantly affected by temperature and time. At low temperatures, dehydration of clay minerals alters pore structure, while at high temperatures and over extended periods, decomposition generates numerous new pores. Initially dense sandstone with high cementation strength exhibits minimal porosity changes under the same heating conditions. It requires high temperatures and prolonged heating to disrupt the cementation structure and significantly increase porosity. Therefore, the initial properties of sandstone must be comprehensively considered in research.

6. Conclusion

(1) This experimental study found that under heating in a muffle furnace, the porosity of sandstone continuously increased with rising temperature, with varying growth rates across different temperature ranges. At a fixed temperature, porosity increased with prolonged heating time, but the growth rate gradually slowed down. On a microscopic level, sandstone transitioned from being dense to loose as the temperature rose. The mechanisms influencing porosity due to heating included thermal stress, mineral phase transformations, and other factors.

(2) The study achieved innovation through comparative experiments across multiple temperature gradients and time intervals, as well as the integration of macroscopic and microscopic techniques. However, it also had limitations, such as sample heterogeneity and constraints imposed by laboratory conditions. Future research will focus on four aspects: reducing errors caused by heterogeneity, conducting multi-factor coupled simulations, establishing quantitative models, and introducing new technologies to deepen microscopic understanding.

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