Mesoscopic Mechanism of Permeability of Coal Rock Mass with Increasing Temperature in the Range of Room Temperature to 350°C

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Engineering research on geothermal development, underground gasification of coal, and heat-injection-enhanced coal bed gas extraction is gaining more and more attention from the international community, and therefore the study of permeability of coal rock bodies under the effect of temperature has become almost a hot spot in the research of rock mechanics and seepage mechanics. However, the relationship between temperature and permeability that has been seen in the literature is different, and the mechanism explanation varies greatly. In this paper, the following conclusions were obtained from an experimental study of the fine-scale structural evolution of coking coal and fine sandstone specimens, using an experimental research method of simultaneous image observation of the pore structure evolution of coal rock samples by online heating. (1) With the increase of temperature, the inner areas of coal and rock mass with both solid particles and pure pores are affected by temperature. The microscopic experiment shows that the gray level of the image changes greatly, that is, the changes in pores are also large. These pores are the roar pores in the coal and rock mass. (2) With the increase in temperature, the solid skeleton of the coal specimen will produce expansion deformation. On the one hand, this expansion deformation will increase the pores between some skeletons and increase the overall porosity of the specimen. On the other hand, it will also reduce the pore area and reduce the overall porosity of the specimen due to the intrusion of the solid skeleton into the adjacent pores. These two phenomena occur at the same time with the increase in temperature. The dominant mode is determined by the type of coal. The physical structure and temperature of the section are affected jointly. (3) When the temperature increases, the porosity of coking coal samples increases first and then decreases, and 180°C is the turning point. The fine sandstone sample shows the law of decreasing first and then increasing, and 210°C is the turning point. (4) When the temperature increases, the smaller the porosity of coal and rock samples, the specimen shows the intrusion of the solid skeleton into adjacent pores, that is, the porosity decreases. After the turning temperature, the porosity increases with the increase of temperature.

1. Introduction

With the development of geothermal resources, underground gasification of coal mines, and coalbed methane mining [1–3], a series of scientific and engineering developments have been highly concerned by domestic and foreign scholars, and a series of experimental and theoretical studies on the permeability of coal rock bodies under the effect of temperature have been conducted [4–7]. Thermally altered sandstones were studied [8–11], and the permeability of sandstone after high-temperature treatment was found to increase by 50%. Homand-Etienne and Houpert [12] found increased rock connectivity and new fractures in dense granites under thermal action. When doing experiments on thermal cracking of rocks, Chen et al. [13] found that the permeability of carbonate rocks increased nearly 10 times at temperatures of 110–120°C. Bing et al. [14] found that high temperatures caused significant changes in the permeability of the rocks.

In recent years, many experiments on the permeability of coal rocks under thermal action have found some special phenomena and laws [15–18]. In the experiments on the permeability of lignite under the effect of temperature and triaxial stress, Hu et al. [19] found that the permeability of coal samples showed a monotonic decreasing pattern in the...
range of room temperature to 300°C with the increase of temperature, although the axial pressure and the surrounding pressure applied to the coal samples always kept constant pressure. Some researchers found that the permeability of granite and sandstone under various temperature and pressure conditions showed fluctuating change patterns such as increase and decrease with increasing temperature [20–23]. When Pan et al. [24] conducted experiments on the permeability of coking coal under the effect of temperature, they found that the permeability of coal samples under specific conditions first decreased and then increased with increasing temperature. Zhang et al. [25] found that there was a sharp increase and then a rapid decrease in the permeability of the specimens when they studied the percolation characteristics of red sandstone at different high temperatures. Yu et al. [26] found that the permeability of coal samples decreased with the increase of circumferential pressure, and the wet permeability of coal samples showed a "V"-shape change at low circumferential pressure, and the increase in temperature led to the volume expansion of solid particles in coal, which reduced the space of pores and fissures. Some researchers conducted experiments on the correlation law of coal sample permeability with temperature and stress and found the same phenomenon and law [18, 27–31]. Xue et al. found that energy rate can be used as a new effective mechanical parameter to analyze and predict the damage and failure characteristics of coal [32]. The fracturing evolution law of coal can be explored from another aspect and the change of permeability can be reflected. Such phenomena must occur simultaneously with heating and fine structure changes, and because the experiments are very difficult, the relevant fine view experiments are not online heating experiments [33–39]. The experimental study of heating and simultaneous online fine-scale observation of coal and fine sandstone gives a finescale mechanistic explanation of such phenomena.

In summary of the above research results, in laboratory experiments, most of the research temperatures are below 150°C, and the study of coal rock adsorption and permeation at higher temperatures is less, and it is not easy to realize the experimental method that can meet the real-time variable temperature observation under fine-scale conditions. Based on this, this paper conducts experiments through real-time online observation with a polarized light microscope retrofitted with a hot stage and simultaneous access to specimen images. The change of pore space inside the specimen is inferred through image grayscale analysis to realize the effective observation of pore space change in coal rock body at fine view scale and analyze the mechanism of its permeability fluctuation change with temperature increase.

2. Experimental Scheme

2.1. Experimental Equipment. A polarizing microscope with a hot stage is used in this paper (Figures 1 and 2), Instrument model is LeicaDMRX. Magnification is 500 times. A heating rate of 3°C/min is adopted for the hot stage. Temperature control accuracy is ±0.1°C. The hot chamber of the hot stage is inertly protected by nitrogen.

2.2. Experimental Sample and Preparation. The coal samples used in the experiment are coking coal and fine sandstone. The coking coal samples were taken from the 2# coal seam samples in Shanxi Coalfield, Fine sandstone is mined from the Liliu mining area in Shanxi Province. Thin sections of coal and rock specimens were processed in the geological laboratory of the Taiyuan University of Technology, after grinding by the grinding machine for the first time, and then by manual grinding, the specimen thickness is 0.3 mm.

2.3. Experimental Method. During the test, first place the test piece with the thickness of 0.3 mm on the hot table, conduct micromagnification observation at room temperature (22°C), take electronic photos, and then start heating at the heating rate of 3°C/min. Each temperature point to be observed is kept constant for 3 minutes under program control. In the range of room temperature to 350°C, the electronic image of the test piece shall be collected every 30°C.

3. Meso Statistical Analysis of Pore Characteristics of Coal and Rock with Increasing Temperature

The permeability of coal and rock is closely related to porosity. By analyzing the two-dimensional image of the specimen, we can count the changes of pores in the image and the area of pores and skeleton hybrid area and then reflect the changes in porosity. The image area depends on the selected specific pixels.
The coal and rock samples were heated from room temperature to 350°C step by step, and the electronic pictures were taken online in real-time for statistical analysis of the grayscale of the pictures.

From the perspective of mesostatistics, coal and rock are composed of pores and a solid skeleton, which is composed of mineral particles with different hardness. When doing so research, we use a very small square grid to segment the coal and rock samples and see the light transmission and reflectivity of each grid; that is, it shows different gray levels. Due to the randomness of solid particle and pore distribution of coal and rock samples, there are both rock solids and pores in each observation subgrid. Therefore, in the same subgrid, the imaging gray level is different with different proportions of solid and pore. When the temperature rises, the solid part in each subgrid expands or changes in shape, resulting in the relative change of the proportion of solid and pore parts, and the gray level of imaging also changes.

During the analysis, the image is divided into 0~255 levels according to the color scale. The specific color scale that can reflect the pore change of the coal rock specimen in the color scale distribution of the coal rock specimen image is defined as the “characterization color scale,” also known as the “characterization grayscale.” The change of the color scale from 0 value to the sum of pixels contained in the characterization color scale at different temperatures is counted, which can reflect the change of pore structure of coal rock specimens caused by thermal expansion. In the part of the image with the color scale below 50, the number of pixels counted at different temperatures is almost unchanged, which reflects that the pure pores or the absolute dominant subgrid of pores in the subgrid of coal and rock specimen hardly change in the process of temperature change. The pixels of 60~100 color scales in the image are affected by temperature, and the sum of pixels changes greatly. The subgrid that just reflects the gray level is the hybrid area of pure pores and solid particles. In this area, the solid particles expand rapidly and change shape with the increase in temperature, resulting in a significant change of pure pores.

From the perspective of seepage engineering, this area is just the roar pore of porous media. The change in pore size will cause a sharp change in coal and rock permeability. Therefore, this paper focuses on the evolution law of the grayscale pore.

### 3.1. Statistical Analysis of Mesoscopic Characteristics of Coke Coal Specimens with Increasing Temperature

The statistics of the experimental results of the coking coal sample are shown in Figure 3. The proportion of the sum of pixels below the gray level of the specimen image gradually decreases. At 120°C in this temperature range, the proportion of the pixels before and after 120°C increases from 5.98% to 6.15% and then begins to decrease to 4.81% at 200°C. It shows that in this temperature range, the specimen is dominated by internal expansion deformation under the action of heat, which occupies the space of the pore part and reduces the porosity of the specimen. There is a slight fluctuation at 120°C, which is not enough to affect the overall change trend of permeability.

In the temperature range of 200°C~350°C, the proportion of pixels representing gray level statistics of the specimen increases monotonously, from 4.81% at 200°C to 9.15% at 350°C. It can also be seen from the observation window of the microscope that the specimen has obvious expansion and deformation as a whole. From the microlevel analysis, the solid skeleton of the specimen will expand with the increase in temperature, but the result of the expansion is that the solid skeleton expands and deforms outward, the porosity will increase, and the corresponding permeability will increase.

### 3.2. Statistical Analysis of Mesoscopic Characteristics of Fine Sandstone Specimens with Increasing Temperature

In Figure 4, at 22°C~200°C, with the increase in temperature, the proportion of the total pixels below the gray level of the specimen image gradually decreases. At 120°C in this temperature range, the proportion of the pixels of the specimen fluctuates. The proportion of the pixels before and after 120°C increases from 5.98% to 6.15% and then begins to decrease to 4.81% at 200°C. It shows that in this temperature range, the specimen is dominated by internal expansion deformation under the action of heat, which occupies the space of the pore part and reduces the porosity of the specimen. There is a slight fluctuation at 120°C, which is not enough to affect the overall change trend of permeability.

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### 4. Analysis of the Change of Pore Mass Size and Shape of Coal and Rock with Increasing Temperature

The previous is to analyze the changes of mesopores and fractures of coal and rock samples under different temperatures from the statistical point of view of representing the pixel sum of the grayscale. The following is to select some typical pore clusters to study the changes in size and shape under different temperatures.
For the electronic pictures of coking coal and fine sandstone specimens at various temperatures, the white part indicates that the pores are relatively dense and the reflection is good, and the dark color indicates that the pores and fissures are developed and the reflection is weak. According to the principle of the equal color scale, circle a fixed area in the image. In this area, compared with solid particles, pores occupy an absolute number. This area is defined as “characteristic pore mass.” The change in the absolute value of the pixel of the characteristic pore mass can reflect the expansion or deformation of the solid skeleton in the adjacent area of the pore mass.

In the whole temperature range, the “characteristic pore group” is always in the microscope window, and the area of the “characteristic pore group” in the image corresponding to 11 temperature points can always be accurately measured. Image processing software was used to set the tolerance of gray level difference to 0, identify and mark the feature region at different temperatures, make statistics of the pixel size contained in the region, and observe and compare the changes in the area.

4.1. Electronic Image of Coking Coal Specimen. Figure 5(a) shows the image of the coal sample at room temperature. The pixels contained in the pore mass are 53076, accounting for 0.73% of the whole image. Figure 5(b) shows the image at 60°C. The pixels contained in the pore mass increase to 67447, accounting for 0.93% of the whole image. Figure 5(c) shows the image at 90°C, and the pixels contained in the pore mass are 73906, accounting for 1.01% of the whole image. Figure 5(d) is an image of 120°C, and the pore mass contains pixels 75104. Figure 5(e) shows the image at 150°C, the area of pore mass decreases, and the pixels included are 51857, accounting for 0.712% of the whole picture. Figures 5(f)–5(h) are imaged at 180°C, 210°C, and 240°C. The characteristic pore mass of the coal sample begins to increase, and the pixel sum is 61428, 64558, and 67373, respectively. From 240°C, the observed characteristic pore mass begins to shrink; that is, the solid skeleton around the pore mass expands towards the center of the pore mass and stops at 300°C, as shown in Figures 5(h)–5(k).

According to the overall analysis of Figure 5, in the temperature range from room temperature to 350°C, there are two peaks in the change of the total pixel of the characteristic pore mass; that is, there are two large fluctuations in the area change of this area, respectively, near the temperature points of 120°C and 240°C. Correspondingly, a trough occurs at 90°C.

Figure 6 clearly shows the change of characteristic pore mass with the sum of pixel points when the temperature increases. The area of characteristic pore mass fluctuates in the range of 0–350°C, and there are two peaks at 120°C and 240°C, there is a trough at 150°C, and the changing trend of characteristic pore mass is consistent with the results of statistical analysis and processing of the whole image according to gray level. They all experienced the fluctuation process from trough to peak, resulting in the corresponding increase or decrease of macropermeability.

4.2. Electronic Image of the Fine Sandstone Test Piece. Figure 7 shows the change of characteristic pore mass of the fine sandstone sample. The total pixel size of the image is 7281900. A characteristic pore mass is defined in the middle area of the image. The shape and size change of the pore mass is analyzed in detail below.

It can be seen from Figure 7 that the fine sandstone image is relatively uniform, the particles are arranged compactly, the scale of pores is not different, and there are no large patches of pores. In the temperature range of normal temperature to 350°C, the area of the pore mass changes violently, from 22°C to 240°C, the area of the pore mass decreases monotonically, and the total pixel decreases from 49073 at normal temperature to 16233 at 240°C, a decrease of 66.9% and then increases rapidly, reaching 43595 at 350°C, which is the same as the number of pixels at normal temperature.

The identification pore pixels number of fine sandstone sample with the increasing temperature is shown in Figure 8. It can be seen from the figure that the pore area of the fine aggregate changes sharply with the temperature of 350°C in the process of heating at room temperature. The area decreases sharply from normal temperature to 240°C, reaches the lowest value at 240°C, and increases rapidly after 240°C, which also leads to the corresponding change of macropermeability.

5. Discussion on the Evolution Law of Pore Mesostructure of Coal and Rock with the Increase of Temperature

Through the gray statistical analysis of electronic pictures, it can be seen that both coking coal samples and fine sandstone samples show the law of porosity fluctuation with the increase of temperature, but the temperature at the turning point is different. Meng et al. [9] concluded from their study on the permeability of fine feldspar sandstone that there is a threshold temperature for the permeability of feldspar fine
sandstone. When the temperature reaches the threshold, the permeability increases greatly. They believe that the thermal expansion of coal and rock mineral particles is caused by the temperature effect, which leads to the mutual extrusion of particles and the closure of primary pores and cracks. At the same time, pore pressure and gas viscosity cannot be ignored at different temperatures. Li Zhiqiang and Xian Xuefu et al. [15–17] also found that permeability fluctuates with temperature in their experiments on the permeability of coal. They explain it by internal and external expansion caused by coal heating, which is consistent with the mesoscopic conclusion of this paper.

When studying the correlation between thermal fracture and permeability of the rock, Zhao Yangsheng, Wan Zhijun, etc., [8] found that the permeability of granite samples fluctuates with the increase of temperature before 350°C. The permeability presents a peak range in the temperature range of 55°C–65°C, 110°C–230°C, 270°C–340°C, and 400°C–500°C. Somerton and Gupta [8] believed that the thermal fracture of rock increases the porosity of coal and rock in a short time, new cracks will be added in the thermal fracture area, and the seepage channel will be opened, and the permeability will increase. In the process of continuous temperature rise, the rock particles with thermal fracture continue to expand, which reduces the crack width and even partially closes, resulting in reduced connectivity and permeability. In the process of continuous temperature rise, the interaction between the local thermal fracture of rock and the expansion of rock particles in the thermal fracture area leads to the existence of peak intervals of permeability with the increase of temperature. In short, under the action of temperature, the expansion of solid particles and the thermal fracture of the solid skeleton make the pore and fracture space in the rock constantly change, resulting in the corresponding change of macro permeability, which is the law of rock temperature permeability coupling.

During the experiment, the coal and rock will be extruded or expanded as the temperature rises. Because the display area of the collected image has no change, the overall gray level analysis of the image can be used to

Figure 5: Microimages of coking coal sample identification pore on the increasing temperature. (a) 22°C; (b) 60°C; (c) 90°C; (d) 120°C; (e) 150°C; (f) 180°C; (g) 210°C; (h) 240°C; (i) 270°C; (j) 300°C; (k) 350°C.

Figure 6: The graph for the identification of pore pixels number of the coking coal sample with the increasing temperature.
reflect the overall porosity change of the specimen, and the conclusion of porosity fluctuation change can be obtained by comparing it with the changes of pixels in the feature area. In the experiment of coke coal and sandstone, the porosity of the sandstone specimen decreases first and then increases, while that of the coke coal specimen increases first and then decreases. From the perspective of image change, the initial porosity is the main reason for this change.

During the statistical analysis, within the range of representation color levels, the data curve changes significantly under high color levels, while the graph line changes gently under low color levels, which is determined by the proportion of statistical pores and solid particles, and is also affected by the total number of pixels. Under the premise that the total number of pixels of the specimen remains unchanged, the higher the color level, the total number of pixels within the statistical range of the representation color level will increase, and the percentage will be more obvious. Selecting four color levels can better reflect the trend of specimen pores changing with temperature.

6. Conclusion

Taking coke coal and fine sandstone as samples, this paper introduces in detail the experimental method of online heating synchronous observation of pore structure evolution of coal samples, makes a detailed analysis of the obtained electronic pictures, and draws the following conclusions:

(1) With the increase in temperature, the inner areas of coal and rock mass with both solid particles and pure pores are obviously affected by temperature. The microscopic experiment shows that the gray level of the image changes greatly, that is, the changes in pores are also large. These pores are the roar pores in the coal and rock mass.

(2) With the increase in temperature, the solid skeleton of the coal specimen will produce expansion...
deformation. On the one hand, this expansion deformation will increase the pores between some skeletons and increase the overall porosity of the specimen. On the other hand, it will also reduce the pore area and reduce the overall porosity of the specimen due to the intrusion of the solid skeleton into the adjacent pores. These two phenomena occur at the same time with the increase in temperature. The dominant mode is determined by the type of coal. The physical structure and temperature of the section are affected jointly.

(3) When the temperature increases, the porosity of coking coal samples increases first and then decreases, and 180°C is the turning point. The fine sandstone sample shows the law of decreasing first and then increasing, and 210°C is the turning point.

(4) When the temperature increases, the smaller the porosity of coal and rock samples. After the turning temperature, the porosity increases with the increase of temperature.

Data Availability

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also form part of an ongoing study.

Conflicts of Interest

The authors declare that they have no conflicts of interest in this work.

Authors’ Contributions

Tao Meng and Xiaoyuan Sun were responsible for data curation. Tingxu Jin investigated the study. Jianlin XIE wrote the original draft. Jianlin XIE reviewed and edited the manuscript.

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