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Quantitative evaluation of the impacts of drilling mud on the damage degree to the permeability of fractures at different scales in coal reservoirs

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ABSTRACT

The current study aimed to investigate the degree of pollution from drilling mud on different scales of fractures in coal reservoirs. Drilling mud for field utilization was prepared in the laboratory and different scales of fractures were generated in coal and rock samples before and after being polluted by the drilling fluid and observed using scanning electron (SEM) and an optical microscope. Using Monte Carlo modelling, the networks of the millimeter (mm), micron- and nano-meter sized fractures, before and after pollution were separately determined. After programming, seepage models of mm, micron- and nano-meter sized fractures were separately constructed using Matlab software. The degrees of pollution of the drilling fluid on the different scales of fractures were calculated according to the seepage principle and compared with the measured permeability of the polluted boreholes. The micron- and nano-sized fractures were more sensitive to drilling fluids compared to the mm-sized and larger fractures. When the original permeability of the coal reservoir was low, different scales of fractures were all greatly polluted by drilling fluids, macroscopically showing high damage to permeability of the coal reservoir. However, when the original permeability of coal reservoir was large, the pollution degrees of micron, and nano-sized fractures failed to be macroscopically observed, having insignificant influences on the permeability of the coal reservoir. The results showed that the combination of the Monte Carlo method and the Matlab numerical simulations can more distinctly reflect the pollution degrees of the drilling fluids on different scales of fracture compared to traditional methods that have been used to test the permeability of coal reservoirs before and after pollution.

1. Introduction

Drilling mud is a drilling fluid that is generally used for drilling boreholes in coalbed methane (CBM) reservoirs. Drilling mud can penetrate into coal seams during drilling causing pollution of coal seams [1–14]. Exploring the pollution degree from drilling fluids to coal seams exerts significance on improving the performance of drilling fluids and reducing damages on coal seams [15–20]. Previous methods for evaluating the degree of pollution from drilling fluids to coal seams mainly include the core flow test method, the method of observing microscopic pores and fissure structures of coal masses, the indirect evaluation method based on expansion rate, a mathematical model method for testing permeability based on Darcy's law, and the combined evaluation method based on permeability recovery rate and desorption ratio.

Based on Darcy's law, the core flow test method can determine the permeabilities of coal reservoirs before and after pollution of fractures by drilling coal cores and simulating various parameters (e.g. temperature, stress and weight on coal reservoirs) to evaluate the pollution degree. The permeability of coal reservoirs is a parameter for comprehensively characterizing the flow conductivity of different scales of fractures. However, the method fails to acquire the pollution degree of drilling fluids for different scales of fractures [21].

The observation method for microscopic pore and fissure structure intuitively evaluates the degree of pollution by observing pore size, volume and fracture filling before and after fractures were polluted using mercury injection, low-temperature liquid nitrogen by optical and scanning electron microscopy. The drilling fluid mostly penetrates into micron-sized and larger fractures whilst the tested pores are generally nano-sized. The difference between the measured and actual polluted scales results in a large error associated with the results [22–30].

The indirect evaluation method based on expansion rate determines the expansion rate of coal seams after being immersed in drilling fluids

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using an expansion rate tester, which fails to quantitatively evaluate the degree of pollution. The mathematical model method of testing permeabilities based on Darcy's law is to establish a mathematical model of the pollution distance according to Darcy's law and drilling parameters to further evaluate the degree of pollution. Generally, the method can macroscopically evaluate impacts on the flow conductivity of fractures [31].

The combined evaluation method based on permeability recovery rate and desorption ratio determines the influence of pollution by testing permeability and desorption amounts before and after pollution of fractures [32–34]. Overall, the rating of the pollution degree by drilling fluids concentrates on a macroscopic scale level. However, fractures in coal reservoirs occur across different scales, and different particle sizes of drilling fluids show differences in degrees of pollution to different scales of fractures.

To accurately characterize the degree of pollution from drilling fluids at different scales of fractures, fractures before and after being polluted by drilling fluids were observed. Using a Monte Carlo method, the network of different scales of fractures was reconstructed and the seepage capacity of the network was quantitatively characterized by programming [35–43]. By comparing the characterization results with the test results of the permeability of the coal reservoirs, the pollution degrees of different scales of fractures in coal were acquired.

2. Experimental

2.1. Materials

Coal samples taken from the Daning Coal Mine in the Qinshui Basin were sawed, drilled and ground into small blocks according to the requirements of the *Measurement Method for Physical and Mechanical Properties of Coal and Coal Samples* (GT/T23561-2009). Afterwards, the blocks were polished and made into coal bricks with the dimensions of 10 mm × 10 mm × 5 mm, and coal pillars with a diameter of Φ50 mm and 100 mm in height. The different scales (including millimeter, mm and micron-sized, fractures) of fractures were observed in the coal bricks.

After polishing 14 coal bricks with the dimensions of about 10 mm × 10 mm × 5 mm, the bricks were divided into two groups and numbered (Nos.1–7 in the first group and Nos. 8–14 in the second group). The original surface was not ground during the polishing to preserve the surface for observation. Polished samples were pretreated.

The prepared drilling fluid contained clay (mainly SiO_2) in which there were Silicon and Oxygen elements that were also found in the sedimentary minerals of coal which was likely to influence subsequent SEM and EDS observation (SEM means scanning electron microscope, and EDS means energy dispersive spectrometer). For this reason, the aim of pretreatment was to remove sedimentary minerals on the surface pores and fissures.

Pretreatment was carried out in the following steps. Samples were immersed in hydrochloric acid to weaken minerals on the surface pores and fissures of the coal. Samples were washed through an ultrasonic water bath and dried to eliminate influences of original sedimentary minerals in the coal. The first group of samples was directly observed as a reference; the second group of samples was observed first, then soaked in the prepared drilling fluid, and placed in a 25 °C incubator during soaking, after soaking for 24 h, and then observed.

By investigating CBM wells in the southeast of Qinshui Basin of Shanxi Province, China, the mineralization degrees and ion content of surface water and water from coal seams were measured. The test results are displayed in Table 1.

As shown in Table 1, the water from coal seams was found to mainly contain $NaHCO_3$. This type of water was therefore used to prepare drilling fluids in the laboratory. By extracting drilling fluids from the drilling site of the SZ-1 well in the Shizhuang south block of the Qinshui basin and analyzing the proportions of each component in the drilling fluid when it contacted the coal seams, the specific formula was obtained as follows:

Surface water + 0.15% polyacrylamide (PAM) + 0.08% $NaHCO_3$ + 8% clay + 0.1% potassium polyacrylate (KPAM).

2.2. Equipment and methods

Based on a Monte Carlo method, the network of fractures with different scales was reconstructed and a seepage model was established by programming. On this basis, the permeabilities of coal samples with different scales of fractures before and after pollution were calculated and compared with the test results of the permeability of the coal pillars. The details are displayed as follows:

2.2.1. Observations of the fractures at different scales

For the two groups of coal samples, mm-sized and larger fractures in the target coal samples were observed using an optical microscope to determine the parameters of fractures. The process of the specific method was as follows. A representative area with uniformly distributed fractures on the surface was selected as the observation object under the optical microscope with an area less than 1 mm × 1 mm. Similarly, a SEM was applied to observe, calculate and record the micron-sized fractures.

2.2.2. Reconstruction of the fracture network

Fractures were generated using a Monte Carlo method. To generate fractures, it is necessary to determine the generation domain and characterize fractures. The specific steps are displayed as follows:

Firstly, the generation domain of the fracture network was determined based on the length of fractures. The length and width of the generation domain of fractures were approximately 6 times the length of fractures. For example, the average length of fractures is l and therefore the size of the generation domain of fractures can be expressed as $6l \times 6l$.

Secondly, it is predicted that fractures are all straight lines. The coordinates of the center and the length of fractures are (x, y) and s, and the angle of strike is α (it is defined as the counterclockwise rotation angle from x-axis to a fracture), and therefore the coordinates of two ends of a fracture are shown as follows:

$$\text{The coordinate of a starting point:}\begin{cases} x_0 = x-(s/2)\cos\alpha \\ y_0 = y-(s/2)\sin\alpha \end{cases}$$

$$\text{The coordinate point of an end point:}\begin{cases} x_0 = x+(s/2)\cos\alpha \\ y_0 = y+(s/2)\sin\alpha \end{cases} \quad (1)$$

Finally, the number of fractures in each group:

$$N = S\cdot\rho \quad (2)$$

where, N, ρ and S refer to the number of fractures, surface density of the fractures and area of generation domain, respectively.

Afterwards, computer programming was conducted to obtain the characteristics of geometric parameters and establish a two-dimensional (2D) model of a random fracture network.

2.2.3. Construction of the seepage model

Some isolated fractures need to be eliminated as they do not play a role in the flow of fluids. According to the relationship of the geometric positions of isolated fractures in the fracture network, isolated fractures were eliminated to further construct the seepage model using Matlab.

The calculation of the permeability of coal reservoirs is based on the following assumptions to simply the simulation process. Firstly, the fluids flow are unidirectional in the fractures, secondly, the width of the fractures in coal and rocks is unchanged, thirdly, the coupling effect between the seepage and stress fields of the fractures is ignored.

Assuming the boundaries surrounding the fracture network model