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Permeability prediction for coal reservoirs and reconstruction of a different scales pore-fractures network

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ABSTRACT

Describing the connectivity of different scaled pore-fractures and quantitatively expressing permeability can provide an important basis for the output degree of the gas. A network for different scales pore-fracture was reconstructed by observing a large number of coal samples, and using software simulation of the Monte Carlo method. A seepage model about the different scales pore-fractures network was established by assigning zero method and using MatLab software. The effect permeability about different scales pore-fractures network was obtained using a two-dimensional seepage equation. Predicted permeability results are compared with the measured permeability results, and the results show that: the dominant order of different scales pore-fractures connected from highest to lowest is millimeters fractures, seepage pores and micron-sized fractures. The contribution of coal reservoir permeability from biggest to smallest is millimeters fractures, micron-sized fractures and seepage pores. Different parameters in different scales pore-fractures have differing influence on permeability. The reconstruction of a different scales pore-fractures network can clearly display the connectivity of pore-fractures, which can provide a basis for selecting migration paths and studying flowing patterns for gases.

1. INTRODUCTION

Coal reservoir permeability is one of the quantitative parameters that characterizes the fractures development degree in coal. Researchers have previously conducted fruitful research examining the relationship between the coal reservoir fractures and permeability, at home and abroad. Through experimental tests about pore size, permeability and porosity, it has been found that the relationship between fracture width and permeability is a factor of 3 (He and Liu, 2011; Feng Zengchao et al., 2007). The relationship between fracture porosity and permeability is proportional (Zhang et al., 2008; Cui et al., 2005). According to the fractal theory, the coal reservoir permeability increases exponentially with an increase of the fractal dimension of the fracture (Barton C C., 1988; Babagagli Tayfun, 2001). The differences between coal reservoir fracture width, length, density, and connectivity result in differences of gas migration speed and mode. Establishing the relationship between fracture porosity and permeability could lead to certain deviations in the process of studying gases. Reconstructing the different scales of the pore-fractures network can more help to more clearly understand and master the flow state of gas in coal (Sisavath et al., 2004; Chen and Feng, 2006). Microscopic fracture information can be extracted by using the image processing method (Chen et al., 2016), and different scales of pore-fractures networks can be reconstructed by using the Monte Carlo method. In order to obtain the different scales of pore-fractures networks and the impact of coal reservoir permeability, the microscopic observation and Monte Carlo pore fissure network reconfiguration method are used. Connectivity and contribution of permeability to different scales of pore-fractures are studied. This can provide the basis for studying gas migration in coal.

2. THE BASIC IDEAS AND METHODS FOR THE RECONSTRUCTION OF DIFFERENT SCALES PORE-FRACTURES NETWORK

Coal reservoir permeability is one of the quantitative parameters that characterizes the fractures development degree in coal.

2.1 Different fracture scales diversion

In order to describe fine distribution characteristics of the pore-fracture, it is necessary to classify the coal reservoir fracture. Based on

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divisions of different scales of pore-fractures in the past, the millimeter scale is called a millimeter scale in millimeter, and the scale between the micron and the millimeter is called micron. Based on B.B decimal division, combined with studying results about Fu Xue-hai etal, seepage pores are greater than 75nm pores.

1.2 The basic ideas concerning the reconstruction of different scales pore-fractures network

In order to reconstruct the different scales pore-fractures network, it is necessary to find the geometrical parameters of different scales pore-fractures in coal samples. Different scales pore-fractures in coal samples were observed and counted using scanning electron microscopy, optical microscopy, and a series of testing instruments. According to the statistical results, the probability distribution model of pore-fractures network was established. Finally, a random pore-fractures network graph was produced based on the principle of the Monte Carlo simulation and using Matlab software.

1.3 Realization method of the reconstruction of the different scales pore-fractures network

- Sample Preparation

Coal samples in Sihe Mine in Shanxi Province were collected and crushed into small pieces. These small pieces were polished and made into briquettes. The sizes of these briquettes are approximately 3cm × 3cm × 2cm. these briquettes were observing. Parts of the briquettes were shown in figure 1.

(a) (b) (c)

Figure 1: Parts of the briquettes.

- The statistics about geometrical parameters of different scales pore-fractures

The geometrical parameters of pore-fractures simulation mainly include density, direction, trace length, and opening degree. First, the uniformly distributed random numbers of the geometrical parameters were generated using statistical data. Second, the other distributed random numbers were generated using a direct sampling method (LU B. et al., 2005; ODA M A. 1988).

$$\begin{cases} b_n = (ab_{n-1} + c)(\mathrm{mod}\, M) \\ r_n = \dfrac{b_n}{M}, n \in N \\ \text{initial value is } b_0 \end{cases} \tag{1}$$

Where: M is the modulus; mod M is the residual value of the modulus; a is a multiplier; c is increments; b0 is the initial value; and rn is uniformly distributed random numbers in the range from 0 to 1.

Table 1: Geometric parameters of pore-fractures.

Millimeter fracture	packet	density (strip/mm²)	Trend (°)		Fracture length (mm)		Fracture width (mm)	
			means	Standard deviation	means	Standard deviation	means	Standard deviation
	1	0.1	77.8	4.2	2.89	0.16	0.00065	0.0002
	2	0.1	156.7	7.8	3.74	0.19	0.00065	0.0002
Micron fracture	packet	density (strip/um²)	angle (°)		fissure length (um)		fissure width (um)	
			means	Standard deviation	means	Standard deviation	means	Standard deviation
	1	0.0004	40.8	1.6	46.1	4.9	0.75	0.02
	2	0.0004	127.4	5.8	92.3	8.6	0.75	0.02
Seepage pore	packet	density (strip/nm²)	angle (°)		fissure length (nm)		fissure width (nm)	
			means	Standard deviation	means	Standard deviation	means	Standard deviation
	1	0.000005	60.3	2.8	531.4	9.3	12.32	2.35
	2	0.000005	136.4	6.2	453.7	12.4	12.32	2.35

When uniformly distributed random numbers were generated, then other distributed random numbers could also be generated. Such as: $x = \mu_x + \sigma_x \times \sqrt{-2\ln(rand)} \times \cos(2 \times \pi \times rand)$,

Where: x is the normally distributed random numbers; rand is the uniformly distributed random numbers in the range from 0 to 1, and so on. Other distributed random numbers were obtained.

The briquettes were observing by the best magnification of the microscope. The direction, length and width of different scales pore-fractures were counted. Statistical geometrical parameters are shown in Table 1.

The center of pore-fractures were uniformly distributed, the tracing length of pore-fractures were normally distributed, the trend of pore-fractures were lognormal distributed, and the opening degree of pore-fractures were normally distributed.

- The reconstruction about different scales of pore-fractures network

1) Generating domain and characterization of pore-fractures

The pore-fractures network was generated via the Monte Carlo method. In order to generate the pore-fractures network, the generating domain and characterization of pore-fractures were needed. The following steps were performed:

(1) The generating domain of pore-fracture network was determined by the pore-fracture length. For example, the average length of fractures was l, so the size of the generating domain about the fracture was $6l \times 6l$.

(2) If pore-fractures were always straight, the center coordinate of pore-fractures was (x, y), the length of pore-fractures was s, trend angle of the pore-fractures was α (defined as the angle from x-axis rotated counter clockwise to the pore-fractures), and the endpoint coordinates of pore-fractures were as follows:

starting point coordinates：

$$\begin{cases} x_0 = x - (s/2)\cos\alpha \\ y_0 = y - (s/2)\sin\alpha \end{cases}$$

end coordinates：

$$\begin{cases} x_0 = x + (s/2)\cos\alpha \\ y_0 = y + (s/2)\sin\alpha \end{cases} \quad (2)$$

(3) The number of fractures in each group was calculated using the following formula:

$$N = S \cdot \rho \text{ or } N = \frac{S}{S \cdot d} \quad (3)$$

Where: N is the number of fractures; ρ is surface density of fractures; S is the generating domain area; s is the length of fractures; and d is average value of fractures spacing.

2) The realization of reconstruction of the different scales of pore-fissure network

According to Table 1, the average length value of millimeter fractures is 3.315mm. Thus the size of generating domain about the millimeter fractures network can be determined to be 20 mm × 20 mm, with the size of analysis domain being 10 mm × 10 mm. The sizes of the generating domain about micron fractures and seepage pores were obtained by the same method, with the sizes being 400 um × 400 um, 3000 nm × 3000 nm, respectively. Sizes of the analysis domain about micron fractures and seepage pores were 200 um × 200 um, 1500 nm × 1500 nm, respectively. According to equation (3), the numbers of each group about millimeter fractures, micron fractures and seepage pores were 40, 64 and 45, respectively.

The Millimeter fracture network models were shown in Figure 2.

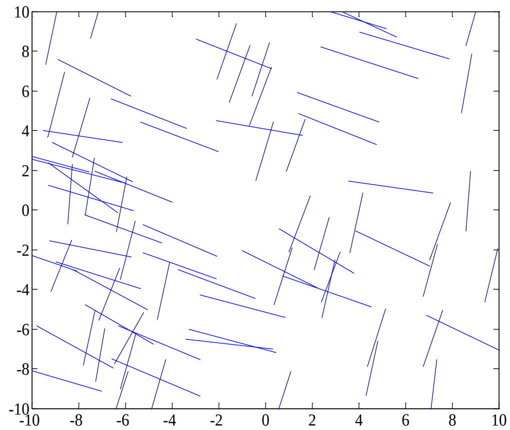

Figure 2: Millimeter fracture network.

3. PERMEABILITY PREDICTION AND VERIFICATION ABOUT DIFFERENT SCALES OF PORE-FISSURE NETWORK

3.1 The establishment of penetration model diagram

The fluid could not flow in generating disconnected pore-fractures, therefore, disconnected pore-fractures should be eliminated. The method of elimination was assigned zero (Min et al., 2004; Xu ZhongJi., 1985; Liu et al., 2007). The intersection of each pore-fissure was calculated using Matlab software, which exists in a lower triangular matrix. While the matrix corresponding position was assigned zero among not intersect fractures, a symmetric matrix was given by the sum of the original matrix. The point of intersection was then found between the boundary and the pore-fractures, and the same place was assigned in another intersection matrix. When an intersection was disjointed or located in boundary extension cord, the corresponding position at the intersection matrix was assigned zero. The boundary node matrix was placed under the inner point of intersection, which was combined into the new total intersection matrix. Those not meeting the requirements of pore-fractures were eliminated by judging the number of intersection points of the pore-fractures. The pore-fractures network model diagram can be obtained by using the pore-fractures intersection connection. The network models are shown in Figure 3.

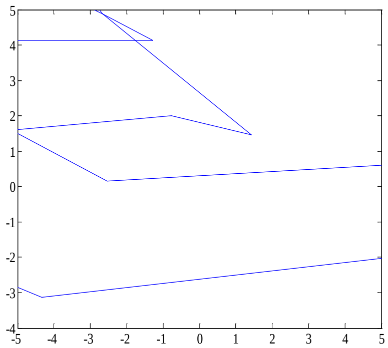

Figure 3: Millimeter seepage model.

3.2 The calculation method for permeability

If the direction of water flowing in fractures was one-way, fracture width in the coal reservoir was not changed. Coupling effects between seepage field and stress field were ignored. According to the second type of boundary conditions combined with the water balance principle, water seepage in fractures was analyzed by establishing a computing matrix. A two-dimensional computing equation of steady flowing was used: (Baghbanan et al., 2008; Chen et al., 2012; He et al., 2013)

$$\begin{aligned} A_1TA_1^TH_1 + A_1TA_2^TH_2 + A_1TA_3^TH_3 + Q_1 = 0 \\ A_2TA_1^TH_1 + A_2TA_2^TH_2 + A_2TA_3^TH_3 + Q_2 = 0 \\ A_3TA_1^TH_1 + A_3TA_2^TH_2 + A_3TA_3^TH_3 + Q_3 = 0 \end{aligned} \tag{4}$$

Where: A1, A2, A3 are the convergence matrix; T the is diagonal matrix; H1 is head vector within a node (m); H2 and H3 are respectively intersection head vector in upper / lower and around bounds of the model (m); Q1 is water sink sources within node (m3); Q2 is flow value about intersection of the upper and lower boundary of the model (m3); and Q3 is flow value around the intersection of the boundary of the model, inflow is positive and outflow is negative (m3).

It can be found from the above equation that:

$$\{H\} = -[D]^{-1}\{Q\} \tag{5}$$

Where: $[D]=\left(A_1TA_1^T\right)$, $[D]^{-1}$ is inverse matrix of $[D]$; $\{Q\} = \{Q_1 + A_1TA_3^TH_3\}$

When H1 was calculated, equation (6) could be obtained combined with equation (4), namely:

$$\begin{cases} Q_2 = -A_2TA_1^TH_1 - A_2TA_2^TH_2 - A_2TA_3^TH_3 \\ Q_3 = -A_3TA_1^TH_1 - A_3TA_2^TH_2 - A_3TA_3^TH_3 \end{cases} \tag{6}$$

The size of the analysis domain was a square of 10mm × 10mm. According to Darcy's Law, permeability coefficient can be obtained as follows:

$$K = \frac{V}{\nabla H/L} = \frac{Q/L}{\nabla H/L} = \frac{Q}{\nabla H} \tag{7}$$

According to the relationships between permeability coefficient and permeability, equation (8) can be obtained:

$$k = \frac{K\eta}{\rho g} \tag{8}$$

Where: η is the dynamic viscosity coefficient of water; ρ is the density of water; g is gravitational acceleration, and k is permeability.

3.3 The prediction and verification of permeability

The matrix equation could be calculated using Matlab software. The permeability coefficient about different scales of pore-fractures can be calculated using the matrix equation. Combined with equation (8), the permeability about different scales of pore-fractures can be calculated. At the same time, in order to verify the accuracy of the predicted results, permeability tests were carried out by collecting coal samples in Sihe mine. The testing results and matrix calculations result were shown in Table 2.

The average permeability was 0.56 mD. The matrix weighted permeability was from 0.172 to 0.531 mD.

Table 2: Comparisons with experimental results and calculated results about permeability in Sihe coal samples.

Sample	Rock samples description	density g/cm^3	Effective porosity %	Permeability(mD)				
				millimeter fractures	micron fractures	seepage pore	Weight calculation	Actual test
SH-1	coal	1.45	3.2	0.19	0.0098	2.85×10^{-6}	0.17198	0.28
SH-2	coal	1.46	3.4	0.31	0.00047	3.69×10^{-5}	0.279047	0.39
SH-3	coal	1.45	3.5	0.46	0.00082	3.3×10^{-6}	0.414082	0.42
SH-4	coal	1.45	2.0	0.59	0.00218	3.6×10^{-5}	0.531218	0.75
SH-5	coal	1.44	2.4	0.23	0.0133	6.1×10^{-6}	0.20833	0.47
SH-6	coal	1.45	3.9	0.55	0.00632	4.5×10^{-5}	0.495632	0.83

Average permeability was 0.352 mD, the calculated results were on the same order of magnitude with the experimental results. Millimeter fractures were major contributors to the permeability, followed by micron fractures, and finally seepage pores were minimal contributors. The simulation results were corroborated with testing results. This paper discusses the influencing law of permeability by different scales fractures parameters.

4. INFLUENCE ON THE VALUES OF THE PERMEABILITY IN DIFFERENT SCALES FRACTURE PARAMETERS

3.1 The influence on the permeability by the density of the fractures

The relationship between the permeability and the density of millimeter fractures is as shown in Figure 4.

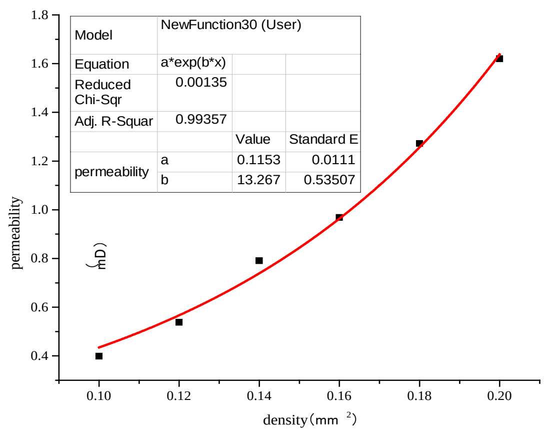

Figure 4: Relationships between the density of millimeter fractures and permeability.

The diversion ability of the fractures increased exponentially with increases of the fracture density. Therefore, increasing density can raise connectivity and permeability.

3.2 The influence on the permeability by the length of the fractures

The relationship between the permeability and the length of fractures is as shown in Table 3.

Table 3: Calculated results for permeability in different lengths about millimeter fractures.

Fissure length (mm)	Permeability coefficient (mm/s)	Permeability (md)
2.87/3.74	4.3157×10^{-6}	0.399
3.09/ 3.94	4.3749×10^{-6}	0.400
3.29/4.14	4.5473×10^{-6}	0.420
3.49/4.34	4.7433×10^{-6}	0.441
3.69/4.54	4.7616×10^{-6}	0.443
3.89/4.74	4.7649×10^{-6}	0.443

The number of nodes and connectivity increased with increases of the length. When the length of the fractures achieves a certain value, the value of the permeability was almost increased.

3.3 The influence on the permeability by the width of fractures

The relationship between the permeability and the width of fractures was found by fitting. It is as shown in Figure 5.

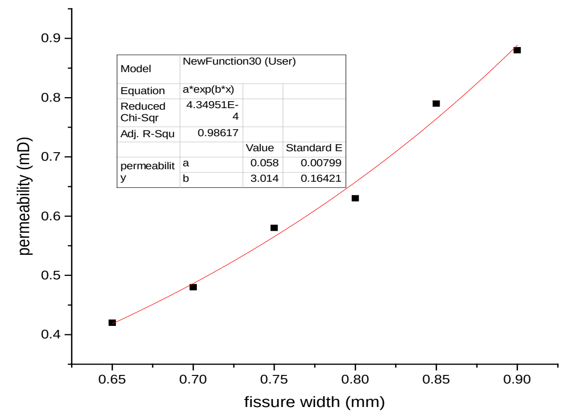

Figure 5: Relationships between the width of millimeter fractures and permeability.

The diversion ability of the fractures was increased with increases in the fracture width and increases in the permeability of the coal reservoir. The relationship between the permeability and the width of the fractures was exponential.

The influence laws of the main parameters of the fractures were such that: density and width in the millimeter fractures and seepage pores have a larger influence on permeability, and the length has little influence on permeability. The density and length of micro fractures have a larger influence on permeability, and the width has little influence on permeability.

5. CONCLUSIONS

According to the simulation about different scales pore-fractures and predicting permeability, the following conclusions can be made:

(1) The networks for different scales pore-fractures were reconstructed using observation and the Monte Carlo method. The networks can clearly show the connectivity between pore-fractures.

(2) The contribution order of different scales pore-fractures on the coal reservoir permeability from largest to smallest are the millimeter fractures, micro fractures, and seepage pores. The advantages of connected paths for different scales pore-fractures from highest to lowest are millimeter fractures, seepage pores, and micro fractures.

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