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Original research paper

Numerical simulation by hydraulic fracturing engineering based on fractal theory of fracture extending in the coal seam☆

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Abstract

According to the fractal characteristics of the porosity of the porous media, as well as the fracture extending in the hydraulic strengthening process, the fractal theoretical relationship between porosity and permeability in the coal seam is established. Furthermore, the fractal calculation models of the fracture robustness and the filtration coefficient of fracturing fluid under the hydraulic fracturing are also built. Based on all of the accomplished studies above, the fracture extended model is set up under the assumed condition of the pseudo-three-dimensional fracture extended model. The geometric parameters of the fracture for the eight CBM wells in the Zhengzhuang block of Qinshui coal basin within Shanxi province were calculated by means of the fractal models. The results show that the fractures' lengths of hydraulic fracture range from 106.8 m to 273.1 m, and the widths range from 3.6 m to 12.7 m in study block. By comparing the calculation results with the different models, it shows that the results of the fractal model fit well with the field measured value, this reflects the applicability of the model to some extent.
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Keywords: Coal reservoirs; Fractal characteristics; Hydraulic fracture; Permeability; Fracture extended model

1. Introduction

Since the 1940s, hydraulic fracturing was successfully adapted in oil and gas wells production in America. Hydraulic fracturing as a stimulation treatment has drawn ever attention. China started to develop the CBM by means of hydraulic fracturing around about the 1990s. At present, hydraulic fracturing is considered the most common and economical and way to improve reservoir environment, flow conductivity, and single well productivity [1,2].

Hydraulic fracture technology aims to generate high conductivity fractures that would promote the permeability of the coal reservoir. The fracture shape and extending laws are generally important technology parameters to evaluate fracture effect. By way of the large-scale process in the CBM development in China, more studies including fracture shape, extending rules, and numerical simulation of the hydraulic fracture et cetera have been carried out, in which many great successes have been achieved in the recent years. On the basis of rock mechanics theory, the direction of the hydraulic fracture, which is perpendicular to the orientation of the minimum in-situ stress, is managed by the stress regime or the relative magnitudes of vertical stress, maximum horizontal stress, and minimum horizontal stress [3]. The said fracture extends in the mentioned direction.

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Although there are a lot of similar characteristics in the coal seam, conventional oil, and gas reservoir, the stress sensitivity of coal seam is resilient due to the natural fractures that grew in the coal seam [4–6]. Hence, the fracture shape differs from the conventional reservoir. The fracture shapes in the coal seam tend to be more random, which means it can form a vertical fracture in a shallow layer and it can also form a horizontal fracture in a deep layer [7,8]. In summary, it's crucial to establish mathematical models accurately for fracture prediction, particularly with the geometric shape and extension law. In the 1970s, the two-dimensional PKN and KGD fracture mathematical models were built and was widely circulated as the classical mathematical models [9,10]. However, the PKN model is more suitable when the length is higher than the height. On the contrary, KGD is the opposite [11]. Then in the 1980s, Palmer created a more seamless pseudo-three-dimensional model with the assumed conditions of the following: (1) a homogeneous formation, (2) the equal stress difference of coal seam roof and floor, (3) elliptical vertical profile, (4) and a one-dimensional flowing model [12]. This has made the application to a smaller vertical extension be excellent. As the research continued, full three-dimensional models were born, and the said models can stimulate the process of the fracture extending in various media effectively. Currently, the construction and application of the full three-dimensional model have undergone a handful of experiments and research [13–17].

For the purpose self-similarity, complexity, and irregularity of pores and fractures in the coal seam, fractal theories have been applied in studying the fractal features of the pores or the fractures formed by geological structure, this subsequently leads to the development of the fractal models of fracture in the 1980's [18–20]. Furthermore, pores and fractures in coals, with varying metamorphic degrees, were analyzed by means of fractal theories, and the relationship between coal properties and fractal dimension were investigated [21–23]. The study shows that fractal dimension of pore volume in coals have a good correlation with coal metamorphism, as the degree of coalification deepens, the value of fractal dimension decreases continuously but its range is generally 2.70–2.90 [24].

Based on the fractal characteristics of pore structure and mechanic parameters of coals, permeability and stress strength factor are calculated using fractal dimension. Then, by means of the Palmer pseudo-three-dimensional fracture model, the hydraulic fracturing prediction model is established with fractal theories. Finally, the main influencing factors of the fracture extending are discussed with the help of the engineering practice of CBM wells in the south of Qinshui Basin, China.

2. Pore fractal feature in the coal seam

2.1. Fractal calculation model of porosity

Generally, the pore shape and porosity in porous media show fractal feature. The self-similar interval has a considerable extent, and its range can reach several magnitudes. In addition, the accumulative volume of the pores is the integration of pore radius distribution density function to the pore radius [25]. The relationship of the pore equivalent radius r and pore accumulative volume $N(r)$, in which the radius is more than the established r in the porous media:

$$N(r) = \int_{r}^{r_{\max}} f(r)dr = ar^{-D} \tag{1}$$

where r, r_{max} are pore radius and maximal pore radius, respectively, μm; $f(r)$ is the pore radius distribution density function; D is the fractal dimension of porosity in the porous media; a is the fractal coefficient which is generally constant.

Moreover, it deduced the following relationship:

$$\frac{dN(r)}{dr} = -aDr^{-(1+D)} \tag{2}$$

Based on the Eq. (2), the definition of porosity in pore media is the porosity ϕ redefined as:

$$\phi = \int_{r_{\min}}^{r_{\max}} \frac{dN(r)}{dr}\cdot \pi r^2 dr = \frac{\pi aD}{2-D}\left(r_{\max}^{2-D} - r_{\min}^{2-D}\right)$$
$$= \frac{\pi aD}{2-D}\cdot r_{\max}^{2-D}\left(1 - \frac{r_{\min}^{2-D}}{r_{\max}^{2-D}}\right) \tag{3}$$

where ϕ is the porosity, %; r_{max}, r_{min} is maximum and minimum pore radius, μm.

2.2. Fractal calculation model of permeability

The research shows that the permeability is relative to the arrangement mode of the particles containing pores, but the relationship is quite complex [26,27]. According to the Poiseuille equation, the length L and sectional area A are calculated without considering the tortuosity for single capillary, the flow is then gained:

$$q = \frac{\pi r^4 (p_1 - p_2)}{8\mu L} \tag{4}$$

The flow at which the pore media let pass at the sectional area; A is deduced [28,29]:

$$Q = \int_{r_{\min}}^{r_{\max}} dq = \int_{r_{\min}}^{r_{\max}} \frac{\pi r^4 (p_1 - p_2)}{8\mu L} aDr^{-D-1} A dr$$
$$= \frac{(p_1 - p_2)}{\mu L}\frac{A\pi aD}{8(4-D)}\left(r_{\max}^{4-D} - r_{\min}^{4-D}\right) \tag{5}$$

where Q is the flow, cm^3/s; p_1 and p_2 are the pressure of the two ends from the column samples of coal cores, MPa; μ is flow viscosity coefficient, mPa·s; A is the sectional area, cm^2; L is the length of the coal column samples, cm.

In combining the law of Dacy's and Eq. (5) the expression of permeability of the fractal porous media is given as follows:

$$K = \frac{Q\mu L}{A(p_1 - p_2)} = \frac{\pi aD}{8(4-D)} r_{\max}^{4-D}\left[1 - \left(\frac{r_{\min}}{r_{\max}}\right)^{4-D}\right] \tag{6}$$

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