Original research paper

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

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Received 22 July 2016; revised 16 August 2016
Available online 13 September 2016

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.

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.
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 geometric shape and extension law. In the 1970s, the two-dimensional PKN and KGD fracture mathematical 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:

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

where $r$, $r_{\text{max}}$ are pore radius and maximal pore radius, respectively, $\mu m$; $f(r)$ 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 $\phi$ redefined as:

$$\phi = \int_{r_{\text{min}}}^{r_{\text{max}}} \frac{dN(r)}{dr} \cdot \pi r^2 dr = \frac{\pi aD}{2-D} (r_{\text{max}}^2 - r_{\text{min}}^2)$$

$$= \frac{\pi aD}{2-D} \cdot r_{\text{max}}^2 \left(1 - \frac{r_{\text{min}}^2}{r_{\text{max}}^2}\right)$$  \tag{3}

where $\phi$ is the porosity, $\%$; $r_{\text{max}}$, $r_{\text{min}}$ is maximum and minimum pore radius, $\mu m$.

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]:

$$Q = \int_{r_{\text{max}}}^{r_{\text{min}}} dq = \int_{r_{\text{max}}}^{r_{\text{min}}} \frac{\pi r^4(p_1 - p_2)}{8\mu L} aDr^{-D-1} Adr$$

$$= \frac{(p_1 - p_2)}{\mu L} A \frac{\pi aD}{8(4-D)} (r_{\text{max}}^{1-D} - r_{\text{min}}^{1-D})$$  \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; $\mu$ 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:

$$K = \frac{QaL}{A(p_1 - p_2)} = \frac{\pi aD}{8(4-D)} r_{\text{min}}^{4-D} \left[1 - \left(\frac{r_{\text{min}}}{r_{\text{max}}}ight)^{4-D}\right]$$  \tag{6}
The range of the pore diameter in coal is wide, it ranged from a nanometer to millimeter level. Thus the minimum pore radius \(r_{\text{min}}\) is far less than the maximum pore radius \((r_{\text{max}})\), which means that \(r_{\text{mid}}/r_{\text{max}} \approx 0\). Thus, the combined Eq. (3) and Eq. (6) can be replaced by the following equation:

\[
K = 10^{-8} \frac{\pi aD}{8(4-D)} \left( \frac{2-D}{10^{-6} \pi aD} \right)^{1/6} \tag{7}
\]

3. Fractal geometry models of fractures extending under the hydraulic fracture

3.1. Fractal calculation model of filtration coefficient

The fracturing fluid loss is mainly affected by filtrate viscosity, compression of formation, and wall-building property of fracture. At present, the fractal fluid selects a clear water or active water in the process of hydraulic fracture of the coal reservoir. The ability to form a filter cake effectively becomes difficult. Therefore, it just needs to consider the effect of the filtrate viscosity and compression of the formation fluid when filter loss is calculated. Thus, the expressions of the overall filtration coefficient are given by the following functions [30,31]:

\[
C_1 = 0.171 \sqrt{K_{\phi} \Delta P / \mu}
\]

\[
C_2 = 0.138 \Delta P \sqrt{K C_1 \phi / \mu}
\]

\[
C = 2C_1 C_2 \left( C_1 + \sqrt{C_1^2 + 4 C_2^2} \right) \tag{8}
\]

where \(C_f\) is the filtration coefficient of fracturing fluid viscosity, m/min\(^{1/2}\); \(C_2\) is filtration coefficient of formation fluid, m/min\(^{1/2}\); \(C\) is overall filtration coefficient, m/min\(^{1/2}\); \(\mu\) is fracturing fluid viscosity, Pa·s; \(K\) is the formation permeability, which is perpendicular to the filtration direction, \(\mu m^2\); \(\Delta P\) is differential pressure of fracture inside and outside, MPa; \(C_f\) is the fluid compression coefficient, MPa\(^{-1}\).

The synthesized formula between the \(C_f\), \(C_2\), and \(C\), as well as the equation of the overall filtration coefficient, is shown as follows:

\[
C = \frac{0.0472 \Delta P \sqrt{\phi K C_f / \mu}}{0.171 + \sqrt{0.0292 + 0.0762 \Delta P C_f}} \tag{9}
\]

Taking the permeability fractal Eq. (7) and Eq. (9), the fractal calculation model of the overall filtration is expressed as:

\[
C = \frac{1.669 \times 10^{-6} \Delta P}{(0.171 + \sqrt{0.0292 + 0.0762 \Delta P C_f})} \left[ \frac{\pi aD C_f \phi} {(4-D) \mu \left( 10^{-6} \pi aD \right)^{1/6} \left( 2-D \phi \right)^{1/2 (4-D) / 2 (2-D)}} \right] \tag{10}
\]

3.2. Fractal geometry model of fracture

In the process of hydraulic fracture, fractures extend by curve shape not by a straight line mode in the underground (Fig. 1). The previous studies found that the distribution of the hydraulic fractures shows fractal characteristics [32]. The relationship between the fracture length \(L\) and yardstick \(\delta_i\) is concluded as following equation:

\[
L(\delta_i) = L_0^{D_f} \delta_i^{1-D_f} \tag{11}
\]

where \(D_f\) is the fractal dimension of the irregular extending fracture; \(\delta_i\) is the yardstick, which is close to a self-similar ratio \(R\).

Hence, it also can be described as follows:

\[
L(\delta_i) = L_0^{D_f} R^{1-D_f} \tag{12}
\]

3.3. Fractal calculation model of fracture toughness

On the basis of fracture mechanics theory, the relationship between the fracture strength \(K_I\) of crack, type I of linear elastic fracture mechanics, and fracture energy \(G_e\) is built as follows:

\[
K_I = A \sqrt{G_e} \tag{13}
\]

where \(K_I\) is the fracture strength factor of coal, MPa·m\(^{1/2}\); \(A\) is the fracture area, m\(^2\); \(A = E/\sqrt{1 - \sigma^2}\) (\(E\) is the elastic modulus of coal, MPa; \(\sigma\) is the Poisson's ratio of rock, %); \(G_e\) is the fracture energy; \(G_e = 2r_s(r_s\) is the surface energy of the fracture area at macroscopic measurement unit, N/m).

In the case of an irregular extending fracture, the fractal expression of the critical extension force is defined [33,34]:

\[
G_{cr} = 2r_s(1/R)^{(D_f-1)} \tag{14}
\]

By means of Eq. (13) and Eq. (14), the expression of the fracture strength is rectified by the following formula:

\[
K_{ID} = K_I(r)^{(1-D_f)/2} \tag{15}
\]

where \(K_{ID}\) is the fracture sturdiness after correction; \(K_I\) is the primary fracture toughness, \(D_f = \lg n/\lg 3\) (\(n\) is the generator quantity, which has the value 3 [32]).

Fig. 1. Fractal shape of crack extension under hydraulic fracturing process [30].
4. Fracture extending model and application of hydraulic fracture in the coal seam based on fractal theory

4.1. Structure of the fracture extending model

4.1.1. Model assumption

In this paper, the purpose of establishing the extending model of the fracture formed was in the process of inducing a hydraulic fracture on coal seams based on the fractal theory, some precondition should be assumed as follows:

(1) The Coal seam is a linear elastic body. Fracture belongs to crack type I of linear elastic fracture mechanics, and plane strain occurs mainly in the horizontal plane.

(2) The mechanical property of coal-bearing formation is homogeneous. However, compared to a coal seam, its roof and floor have different mechanical parameters, such as elastic modulus, Poisson’s ratio, and fracture toughness, but there are same ground stress and elastic parameters in the same strata.

(3) The fracturing fracture is vertical, this always shows elliptic shape in the profile terms, and it also takes the shaft as the axis-symmetric distribution.

(4) The difference in the stress between the roof and floor of the coal seam is unchanged, and the stress is uniformly distributed.

(5) Fluid in the way in which the fracture shows one-dimensional flow mode and the fracture fluid is incompressible.

4.1.2. Model structure

4.1.2.1. Continuity equation

In the process of fracturing, the fracturing fluid injection and loss obey the Law of Mass Conservation. According to the principle of volume balance, it can be concluded that the flow changes, which pass a vertical fracture at any time, equals to the sum of fracturing fluid loss speed at unit length and change rate of vertical profile area. Therefore, in the injection process of fracturing fluid, the continuity equation of fluid migration at fractal theory, some precondition should be assumed as follows:

\[ \frac{dq(x,t)}{dx} = \frac{2HC(x,t)}{\sqrt{t - t_p(x)}} + \frac{dA(x,t)}{dr} \]  

(16)

where \( q(x,t) \) is the fluid flow of \( x \) m placed in the fracture at time \( t \), \( m^3/min \); \( A(x,t) \) is the sectional area of \( x \) m placed in the fracture at time \( t \), \( m^2 \); \( H \) is the coal seam thickness, \( m \); \( C \) is the overall filtration coefficient of the \( x \) m place in the fracture at time \( t \), \( m/min^{1/2} \); \( t_p(x) \) is the filtration start time of \( x \) m place in the fracture, min.

Calculating the fractal permeability of the Eq. (7) into Eq. (16), the continuity equation of fluid migration at \( t \) time is given as:

\[
\frac{dq(x)}{dx} = \frac{2H}{\sqrt{t - t_p(x)}} + \frac{dA(x,t)}{dr} \times \frac{1.335 \times 10^{-5} \Delta P}{\sqrt{(3-D)C_f (\pi(3-D)\phi)^{1/2(3-D)}} + \frac{dA(x,t)}{dr} \times \frac{10^{-6}aD}{C_f} \]  

(17)

4.1.2.2. Pressure drop equation. Utilizing the referred pressure drop equations of the fluid flow in a parallel plate and ellipse pipe by Nolte, a pipe shape factor \( \Phi(n) \) was introduced. The pressure drop equation in the fracture length direction was acquired [35], in regard to Newton fluid of ellipse fracture section, which means \( \Phi(1) \approx 3\pi/16 \).

\[
\frac{dp(x,t)}{dx} = -\frac{64\mu q(x,t)}{\pi h(x,t)w(x,0,t)^3} 
\]  

(18)

where \( h(x,t) \) is the fracture height of \( x \) m placed in the fracture at the time \( t \), \( m \); \( w(x,0,t) \) is the maximum cross-sectional width of \( x \) m placed in the fracture, \( m \).

4.1.2.3. Fracture height equation. Fracture height is constantly changing while the fracture is extended in the process of the hydraulic fracture. However, in a shorter extending length, the fracture height is nearly invariable. Based on the equation of Rice stress intensity factor, by means of fourth-order Runge-Kutta method, taking into account the corrective fractal calculation model of the fracture toughness (Eq. (15)), the fractal calculation model of the fracture height at any time is built as follows:

\[
\frac{dp(x,t)}{dx} = -\frac{64}{\pi} \frac{q(x,t)\sigma}{\epsilon(x,t)w_0^3(x,t)} \left[ \frac{K_I(r)^{(1-D)}/2}{\sqrt{2\pi h^3(x,t)}} \right] - \frac{2}{\pi} \frac{(S_2 - S_1)}{h(x,t)} \frac{H}{\sqrt{h^2(x,t) - H^2}} \]  

(19)

Then:

\[
\frac{dh(x,t)}{dx} = \frac{64}{\pi} \frac{q(x,t)\mu}{\epsilon(x,t)w_0^3(x,t)} \]  

\[
e(x,t) = \frac{K_I(r)^{(1-D)}/2}{\sqrt{2\pi h(x,t)}} - \frac{2}{\pi} \frac{(S_2 - S_1)}{h^2(x,t) - H^2} \]  

where \( K_I \) is the corrective rock fracture toughness, \( MPa\cdot m^{1/2} \); \( S_I \) is the minimal ground stress of coal, \( MPa \); \( S_2 \) is the minimal ground stress of coal seam roof and floor, \( MPa \); \( \sigma \) is rock Poisson’s ratio, %.

4.1.2.4. Fracture width equation. Compared to oil and gas reservoirs, the coal seam is thin. Not to mention, the stress difference of coal seam roof and the floor is small and almost insignificant. Therefore, it contemplates approximatively that fracture of geometrical shape in the vertical profile is
proportion to the coal seam center (Fig. 2). The distribution of the static pressure \( p(y) \) in the fracture internal face is presented at the following equation:

\[
p(y) = \begin{cases} 
    p_f - S_1 & |y| < H/2 \\
    p_f - S_2 & |y| > H/2
\end{cases}
\]

where \( p_f \) is net pressure in the fracture, MPa; \( y \) is the extending height from fracture center to up, m.

According to the plane strain condition put forward by England and the Green, the relationship between the center provides a maximum width of \( x_m \) placed along the fracture length and normal stress of slotted wall can be obtained \[36\]:

\[

w_0 = \frac{2(1-\mu^2)h(x)}{E} \left\{ \frac{p_f - S_1}{S_2 - S_1} \left[ \arccos \eta' \right. \right.
\]

\[

\left. - \eta' \ln \left( 1 + \sqrt{1 - \frac{\eta^2}{\eta^2}} \right) \right\} \quad \text{(21)}
\]

where \( \eta' = \frac{h_m}{h(x,m)} \) is dimensionless quantity.

### 4.2. Model application

#### 4.2.1. Coal seam characteristics in the study area

Zhengzhuang block is located in the Jincheng, the south of Qinshui Basin, which is the most active and successful CBM exploration and development area in China. It is located in the tectonic block of the Qinshui Depression, as well as the south of the Zhangshang-Wuxiang-Yangchong fold zone with the strike direction of NNE. Due to the effects of the Sitou Fault in the east and the Houchengyao Fault in the southeast, a total tectonic setting in the south is higher than that in north, showing tectonic framework of two-depression and one-uplift. Based on this geology structure, a series of folds including anticlines and synclines in the NE direction showed an alternative distribution. In addition, 119 columns collapsed were then disclosed in the geological drilling and seismic exploration. Major minable seams in the block are No.15 coal seam in the Carboniferous Taiyuan Formation and No.3 coal seam in the Permian Shanxi Formation. Gas-bearing area proved is 692 km² in the block. The prediction of the CBM resource reserve is about \( \frac{1612}{10^8} \) m³, among of which \( 700 \frac{10^8}{10^8} \) m³ is classified as the proved reserves. No.3 coal belongs to the anthracite of high metamorphic degree. The maximum vitrinite reflectance ranges from 3.29% to 3.98%, with the average being 3.63%. The burial depth of coal seam No.3 changes from 350 m to 1400 m. There were more coal seams buried in between 500 m and 1100 m, totally showing the distribution laws of the burial depth in the north is deeper than that in the south. The coal seam presents that the distribution trend of the thickness being thick in the northwest and southeast, but thin in the middle part, which the thickness of the coal seam ranges from 1.15 m to 7.39 m, and the average is about 4.95 m. The actual measured gas content is 6.05–30.13 m³/t, and the average is about 20.71 m³/t.

#### 4.2.2. Simulation analysis

Based on the fracture extending fractal model which is built during the study, the referred construction and reservoir parameters of 8 CBM evaluation wells in the Zhengzhuang block took place (Table 1). The fracture length and height after

<table>
<thead>
<tr>
<th>Table 1</th>
<th>The main parameters of some CBM wells in Zhengzhuang block.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
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<tr>
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<td>Calculated results</td>
<td>Permeability/(×10⁻³ um²)</td>
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<td></td>
<td>Overall filtration coefficient/(m/min²)</td>
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</table>
fracturing were calculated by taking porosity fractal dimension of 1.70, the fractal coefficient is out of 10^6 \cite{29,37}, and the generator quantity of n being 3\cite{32}. In order to compare the studies, the fracture length is calculated and compared with the actual results by combining classical PKN, KGD dynamic models, and single fracture extending the model of high-rank coal hydraulic fracture constructed in the document \cite{3}(Table 2).

The result from Table 2 suggests that the fracture length calculation result of the PKN model is less than the field measured values, and the average value of error has reached 88.3\%. The acquired result of the KGD model had great changes with the average error being 58.6\%. The length average error of the model calculation in document 3 and this study are 42.0\% and 20.3\%, respectively. Comparing the results mentioned, it concludes that the length average error based on the PKN model is the largest, but this research is smallest. It means that the prediction of this research is more accurate. Additionally, the fractal model of the fracture extending in this study was set up under the establishment of pseudo-three-dimensional fracture prediction model. Therefore, the fracture height dynamic change and the effect of the fracture length are considered in the fracturing process. It also proves that this model has better applicability.

5. Conclusions

(1) According to the relationship between fractal characteristics in the porous media and the porosity, as well as the permeability, the fractal calculation models of both the porosity and permeability in coal seam are established. The combination in the fractal feature of the fracture extending shape and the effecting factors of the fracture fluid loss during the hydraulic fracturing, the fractal calculation models of the fracture toughness, and overall filtration coefficient are defined.

(2) On the foundation of the pseudo-three-dimensional fracture extending model, and in line with the reservoir physical parameters and fractal calculation model of filtration coefficient, it has built the fracture extended model which is based on fractal theories.

(3) By means of taking 8 evaluation wells in the Zhengzhuang block to apply the fractal model of this study, the length and height of fracture are calculated. The results show that the fractures' lengths of hydraulic fracture vary from 106.8 m to 273.1 m, and the widths range from 3.6 m to 12.7 m in study block. Through comparing the calculation results with different models, it shows the results of the fractal model fit well with the field measured value, which reflects the effectivity of the model to some extent.

Foundation item

Supported by National Basic Research Program of China (41372162); Program for Science & Technology Innovation Teams in Universities of Henan Province, China (14IRTSTHN002).

Conflict of interest

The authors declare no conflict of interest.

Acknowledgements

The authors would like to thank the program help of Coalbed Methane Company of Huabei Oilfield Company, PetroChina.

References


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<td>error/%</td>
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Liuren Li, Shiyi Yuan, Yongle Hu, A new model for describing the relationship between the permeability and the porosity of fractal porous media, J. Xi’ an Shiyou Univ. 25 (3) (2010) 49–51, 74.


Tao Tao Luo, Coal Rock Characteristics and Fracturing Methods for Qinshui Reservoir, Chengdu University of technology, Chengdu, 2010.