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Impact of Coal Orthotropic and Hydraulic Fracture on Pressure Distribution in Coalbed Methane Reservoirs

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Abstract: Coalbed methane (CBM) shows tremendous in situ reserves, attracting a great deal of research interests around the world. The efficient development of CBM is closely related to the dynamic pressure distribution characteristics in the coal seam. As the dominant component of the geological reserve for CBM, the adsorption-state gas will not be exploited until the local coal pressure becomes less than the critical desorption pressure. Therefore, although the CBM reserve is fairly large, the production performance is generally limited, with a poor understanding of the dynamic pressure field during the CBM production. In this work, in order to address this issue properly, the coal's inherent properties, the coal's orthotropic features, as well as artificial hydraulic fracturing are considered, all of which affect pressure propagation in the coal seam. Notably, to the current knowledge, the impact of coal's orthotropic features has received little attention, while the coal's orthotropic features are formed during a fairly long geological evolution, changing the dynamic pressure field a lot. Numerical simulation is performed to shed light on the pressure propagation behavior. The results show that (a) coal's orthotropic features mitigate the depressurization process of CBM development; (b) the increasing length of a hydraulic fracture is helpful for efficient decline in the average formation pressure; and (c) there exists an optimal layout mode for multi-well locations to minimize the average pressure. This article provides an in-depth analysis upon pressure distribution in CBM reservoirs under impacts of coal orthotropic feature and hydraulic fractures.

Keywords: coal orthotropic; hydraulic fractures; CBM; production; pressure propagation

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1. Introduction

China is rich in CBM resources. However, due to the high ground stress, high gas pressure, high gas content, low coal seam permeability, high degree of metamorphism, and complex geological structure in China's coal mines and with the increasing depth of mining, these conditions are extremely unfavorable for underground CBM mining [1–3]. Underground CBM development technology is an important link in the research of CBM development and utilization in China. At the same time, it is also an important part of unconventional natural gas development in China. Its large-scale development and utilization are of great significance for comprehensive energy utilization, high-efficiency coal mining, environmental pollution prevention, and gas mine disaster control [4–11]. Therefore, in order to improve the resource utilization of gas and reduce the occurrence of mine disasters, it is of great significance to improve the efficiency of borehole gas drainage [12]. In this regard, under the guidance of the idea that using the heterogeneous permeability of a coal seam and coal seam fracturing to produce fractures, the desorption rate of CBM can be increases, facilitating mining.

In this study, we mainly study the characteristics of coal seam pressure distribution under the condition of coal seam heterogeneity. The focus of discussion is the influence of permeability changes in two directions of the coal seam's face cleat and the end cleat on coal seam pressure. In the plane range, the coal seam's face cleat is orthogonal to the end cleat.

In other words, in the coal seam plane, the orthogonality of the coal seam is represented by changing the permeability of the directions of the face cleat and the end cleat. In the following research, the anisotropy and heterogeneity of coal seams are discussed based on plane, that is, the coal's orthotropy.

According to the gas parameters of a coal seam's working face based on various geological conditions in a coal mine and gas occurrence conditions in a coal seam, several researchers have studied the influence of negative extraction pressure, borehole layout, and permeability on the gas flow rate of a 100 m borehole and compared it with the measured value on site [13–17]. For the problem of permeability of gas extraction, Hao et al. put forward a permeability enhancement technology with HCAF (hydraulic-cavitation-assisted fracturing). In coal seams, HCAF reduces the fracture initiation pressure to less than 15,000 kPa and increases the effective radius from 8 m to 12 m [18]. The experimental results of Cheng et al. show that the closure of hydraulic fractures significantly inhibits the permeability enhancement of the hydraulic fracturing of coal seams and leads to the permeability of fractured coal samples being significantly lower than that of hard rocks (such as shale and sandstone). By changing the fracturing conditions of coal seams, the permeability of coal seams can be increased, and the extraction efficiency of coalbed methane can be improved [19]. Tang et al. have improved CBM extraction by stimulating the pores and cracks of coal seams through ultrasonic NMR waves to improve the permeability of coal [20]. According to the integration of hydraulic grooving (HS) and hydraulic fracturing (HF), when CBM extraction is completed, the disturbance range of a coal seam in a single drilling is increased and the CBM extraction efficiency is significantly improved [21]. Zuo et al. put forward the fracturing technology in the non-structural area divided by geological structure, and the permeability of the coal seam increased sharply. This mode will promote the effectiveness of natural gas exploitation, effectively improve the concentration and flow rate of coalbed methane extraction, and shorten the exploitation time [22].

Cleaving is a natural fissure commonly developed in coal seams. Cleaving generally occurs in two groups perpendicular to each other or roughly perpendicular to each other and is divided into surface cleaving and end cleaving [23]. Experimental data show that the ratio of surface cleft to end cleft permeability is between 1.2 and 9 [24–27], showing significant heterogeneity. Song et al. proved that the anisotropy and heterogeneity of coal affect the gas seepage law around the slit and borehole by considering the cross-coupling effect of the coal stress deformation field and the gas seepage field through anisotropy and heterogeneity [28]. The simulation results of Lou et al. show that the methane extracted from drilling holes perpendicular to the dominant direction of permeability is much larger than that extracted from drilling holes parallel to the dominant direction of permeability [29]. The methane flow in a coal seam has very obvious anisotropic characteristics. Wang et al. have studied the anisotropy of shale porosity and diffusivity, proving that the diffusivity parallel to the cushion direction is much higher than that perpendicular to the cushion direction, indicating that shale blocks are inhomogeneous and that the cube method is more suitable for studying the anisotropy of heterogeneous rocks [30]. Some studies have shown that, for some coals, the expansion/contraction shows strong anisotropy, with more expansion in the direction perpendicular to the cushion than in the direction parallel to the cushion. For coal with strong anisotropic swelling, anisotropic swelling and permeability models are used to describe the coal permeability behavior of the primary coalbed methane and the enhanced coalbed methane recovery process more accurately [31]. In the anisotropic permeability model put forward by Pan et al., using the permeability anisotropy of dry coal bed methane production in a series of numerical simulations it is shown that when the permeability is equal to the isotropic permeability, the permeability anisotropy had little impact on the rate of gas. However, under the influence of the distribution of pore pressure and gas content and of the results with multiple vertical wells, dry coal bed methane production may have made sense [32]. In view of the current situation of the low permeability and difficult mining of coal seams and the technical problems of safe and efficient mining of low permeability and high gas seam groups, Yuan took the Huainan mining area as the main experimental research base and innovated the theory and technology of gas extraction by pressure relief mining to solve the major technical engineering problems of co-mining coal and gas [33].

Although there are many research results on the problems related to coalbed methane extraction at present, the law of coalbed methane distribution under the simultaneous action of coalbed fracturing and heterogeneity is not clear. In view of this, this paper uses an independently developed numerical simulation program to carry out the study of coalbed methane pressure under the joint action of coalbed heterogeneity and fracturing. This paper first analyzes the distribution characteristics of coalbed pressure force under a single drilling hole in the process of extracting coalbed methane and is then extended to the distribution law of the coalbed pressure force field under multi-well extraction, so as to provide theoretical support for reasonably arranging drilling holes and improving extraction efficiency.

2. Method

This study utilizes MATLAB software to study the coal seam pressure force field. The data visualization display and analysis of the coal seam pressure field at the bottom of pumping well are carried out by using MATLAB software. Firstly, the "mesh" command is used to generate the grid. The extraction area with the grid range of 100 m $\times$ 100 m is used, and then the points on the grid are used to calculate the CBM pressure of the corresponding points. Finally, the mesh command is used to generate the three-dimensional view, and then the "view" command is used to show the two-dimensional plan in the X and Y directions. In this study, when the coal seam anisotropy coefficient is equal to 1, it means that the permeability in the direction of the coal seam's face cleat and end cleat is equal and shows homogeneity. When the coal seam anisotropy coefficient is greater than 1, it means that the permeability in the X direction is greater than that in Y direction, and the coal seam shows heterogeneity. In the following study on the distribution of the coal seam pressure force field, β represents the anisotropy coefficient of the coal seam and shows the change in the homogeneity and heterogeneity of the coal seam by changing the size of the anisotropy coefficient. The parameters and their values involved in this study have been provided in Tables 1 and 2.

Table 1. The parameters used for the case without fractures.

Parameters	Value	Unit
Bottom hole pressure	100	kPa
Production of gas	0.5	m^3/min
X direction range	−100:0.1:100	m
Y direction range	−100:0.1:100	m
Thickness of the coal seam	1	m
Gas viscosity	1	mPa $\times$ s
Permeability of coal	1	mD
Shaft radius	0.1	m
The range of anisotropy coefficient	1–9	/

In this work, the permeability difference in the direction of the face cleat and end cleat is emphasized, and that at the vertical direction is overlooked. Thus, unlike the definition of permeability in homogeneous reservoirs, the permeability in this article, focusing on CBM reservoirs, has the following expression:

$$K = \begin{bmatrix} K_x & 0 \\ 0 & K_y \end{bmatrix} \quad (1)$$

The basic continuum equation is:

$$div\left(-\frac{1}{\mu}K \times gradp\right) = 0 \quad (2)$$

After further derivation over Equation (2), the following equation can be obtained:

$$K_x\frac{\partial^2 p}{\partial^2 x} + K_y\frac{\partial^2 p}{\partial^2 y} = 0 \quad (3)$$

Equations (1) and (3) are the primary differential equations for fluid seepage in heterogenous reservoirs. Then, coupling necessary boundary conditions, such as the closed boundary condition or constant-pressure boundary condition, as well as calculation formulas for fluid physical properties, the differential equations can be solved. As the technical content is dedicated to revealing the impact of heterogeneity, details about the auxiliary equations are not available in this context, which are easily accessed in related references.

Table 2. The parameters used for the case with fractures.

Parameters	Value	Unit
Bottom hole pressure	100	kPa
Production of gas	0.5	m^3/min
X direction range	−100:0.1:100	m
Y direction range	−100:0.1:100	m
Thickness of the coal seam	1	m
Gas viscosity	1	mPa × s
Permeability of coal	1	mD
The range of fracturing half-length	5–20	m
The range of anisotropy coefficient	1–9	/

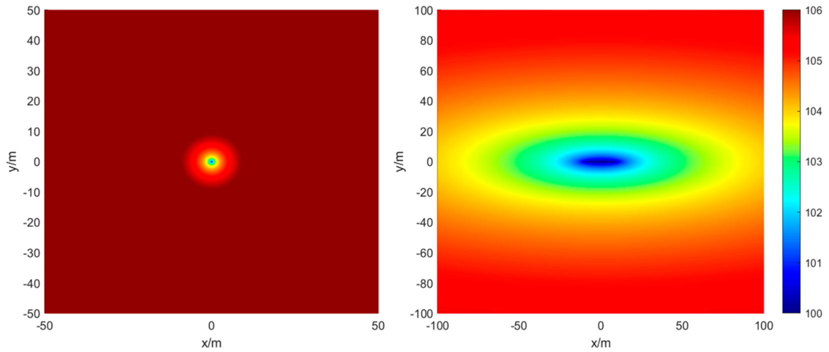
3. Results and Discussion

3.1. Impact of Fracture Length in Homogeneous Coal Seam

First, we discuss the case when the anisotropy coefficient of the coal seam is equal to 1. It means that the coal seam shows homogeneous permeability. Considering the influence of the construction methods of mine gas drilling (fracturing and unfractured) on the flow field, we then use MATLAB software to study the dynamic flow field when fracture drilling to extract a homogeneous coal seam and compare the distribution diagram of the coal seam gas pressure field without fracturing, as shown in Figure 1. Figure 1a shows the distribution of the CBM pressure field of an unfractured homogeneous coal seam, showing a circular pressure drop distribution centered on the borehole, and the average value of the CBM pressure is 107.76 kPa. Figure 1b shows the distribution of the pressure field of a homogeneous CBM after fracturing (fracturing radius is 10 m). From Figure 1, we can see the elliptical pressure drop distribution centered on the borehole. The average CBM pressure is 104.43 kPa. Compared with the distribution of homogeneous CBM without fracturing, the CBM pressure is reduced by 3.1%, which has a good pressure drop effect.

From the above comparison, it can be seen that fracturing has a good effect on the pressure drop in the coal seam. However, whether the change in the fracturing radius has a linear relationship with the pressure drop effect needs to be further studied. Therefore, when the value of the anisotropy coefficient is 1, the change law of the coal seam's pressure drop during fracture drilling and extraction is studied by changing the half-length of the fracture in the X direction of the coal seam (i.e., L = 5 m, L = 10 m, L = 15 m, L = 20 m). As shown in Figure 2, the pressure field distribution maps of the four coal seams have an oval pressure drop distribution centered on the borehole. In the process of increasing the half-length of the borehole fracture from 5 m to 20 m, the pressure drop effect in the

X direction is greater and more obvious than that in the Y direction. According to the calculation of MATLAB, the influence law of the fracturing radius on the CBM pressure is shown in Figure 3 The average pressure drop of the CBM decreases from 105.35 kPa to 102.98 kPa. With the half-length of fracture increasing in the homogeneous state of the coal seam, the average pressure of the CBM decreases gradually. Therefore, increasing fracturing during CBM drilling and extraction can obtain a better depressurization effect, significantly improve the efficiency of CBM extraction, and have reference significance for the visualization of CBM force field distribution data.



(**a**) (**b**)

Figure 1. Pressure field distribution of a single borehole coal seam in homogeneous state: (**a**) Unfractured coal seam, (**b**) Coal seam fracturing.

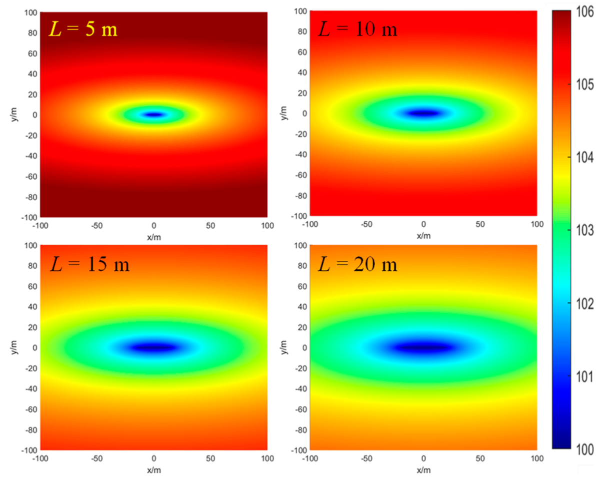


Figure 2. Pressure field distribution of single borehole coal seam under homogeneous fracturing.

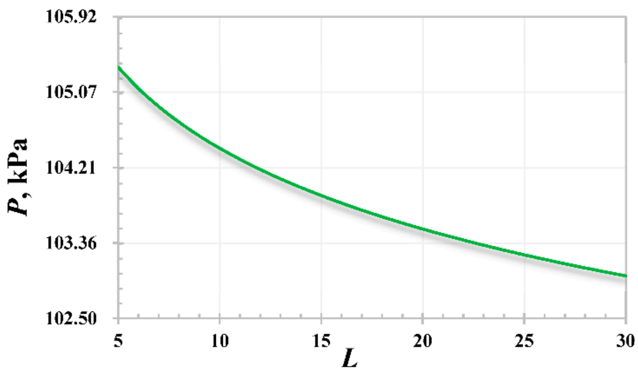


Figure 3. Effect of fracturing radius on CBM pressure.

3.2. Impact of Heterogeneity for Unfractured Coal Seam

The anisotropy change in the coal seam is carried out in the unfractured state, and the distribution of the coal seam's pressure field is studied. The anisotropy coefficient of the coal seam is adjusted (i.e., $\beta = 1$, $\beta = 3$, $\beta = 6$, $\beta = 9$), which makes the coal seam show the characteristics of homogeneity or heterogeneity. As shown in Figure 4, when the anisotropy coefficient is equal to 1, the coal seam shows homogeneity, which is similar to the effect of Figure 1a. When the anisotropy coefficient is not equal to 1, the coal seam shows heterogeneity, and the pressure drop effect shows an elliptical distribution when extracting CBM. It can be seen that the pressure drop effect in the X direction is obviously better than that in the Y direction.

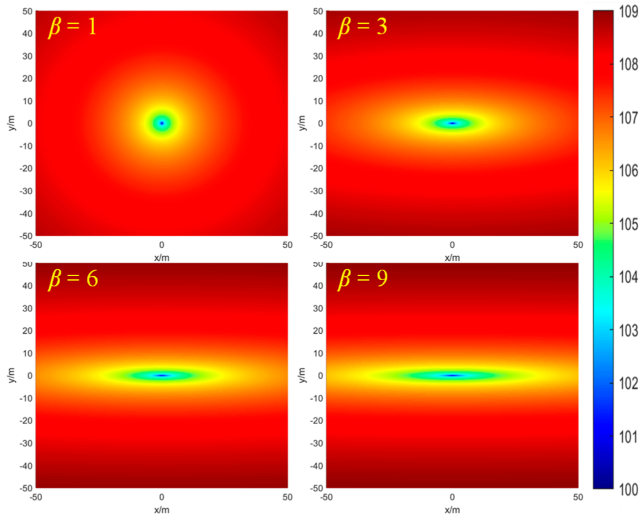


Figure 4. Distribution of pressure field in homogeneous and heterogeneous coal seams without fracturing.

With the variation in anisotropy coefficients from 1 to 9, the distribution of the coalbed pressure field changes from circular to elliptical, and the elliptical pressure drop effect tends to flatten. The pressure drop effect in the X direction becomes larger and larger, while the pressure drop effect in the Y direction becomes smaller and smaller, showing the heterogeneity of CBM extraction. The average value of the CBM pressure calculated by MATLAB shows that the average value of CBM pressure increases with the increase in the anisotropy coefficient. As shown in Figure 5, the pressure can be increased from 107.76 kPa in the homogeneous state to 107.81 kPa when the anisotropy coefficient is 10. The average value of CBM pressure increases, and the pressure drop effect decreases. Therefore, the heterogeneity of a coal seam is not conducive to the extraction of CBM in the unfractured state.

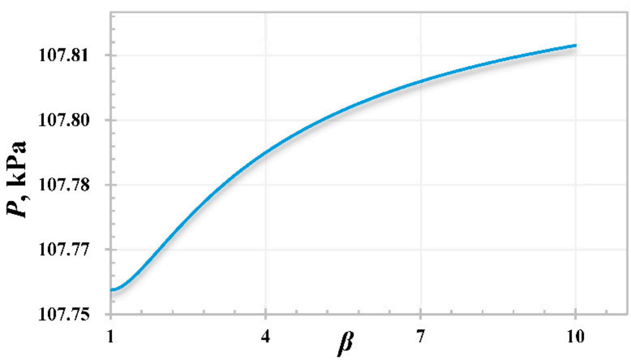


Figure 5. Effect of anisotropy on CBM pressure.

3.3. Impact of Simultaneous Change in Fracture Length and Anisotropy Coefficient

Considering the two factors affecting the pressure field of a CBM extraction borehole, the anisotropy coefficient and the half-length of the borehole fracture, a dynamic study of the flow field during that fracturing borehole extraction of a heterogeneous coal seam is carried out. When the anisotropy coefficient is equal to 3, the coal seam shows heterogeneity. By changing the half-length of the fracture in the X direction of the coal seam (i.e., L = 5 m, L = 10 m, L = 15 m, L = 20 m), the variation law of the coal seam pressure field during fracture drilling and extraction is studied. As shown in Figure 6, under the joint action of the anisotropy coefficient and the half-length of the borehole fracture, the distribution of the coal seam's pressure drop is elliptical, and the pressure drop level is more obvious. Moreover, during the change in the fracture half-length from 5 m to 20 m, the pressure drop area in X and Y directions of coal seam pressure field distribution increases. The average pressure of the CBM decreased from 105.35 kPa to 103.51 kPa. Through MATLAB calculation, the pressure drop law of the coal seam in a heterogeneous fractured reservoir shown in Figure 7 is obtained. The figure shows that when the anisotropy coefficient is constant, the average pressure of CBM decreases with the increase in the fracture's half-length. Therefore, increasing the half-length of coal seam fracturing is more conducive to the reduction in coal seam pressure and the extraction of coal seam gas.

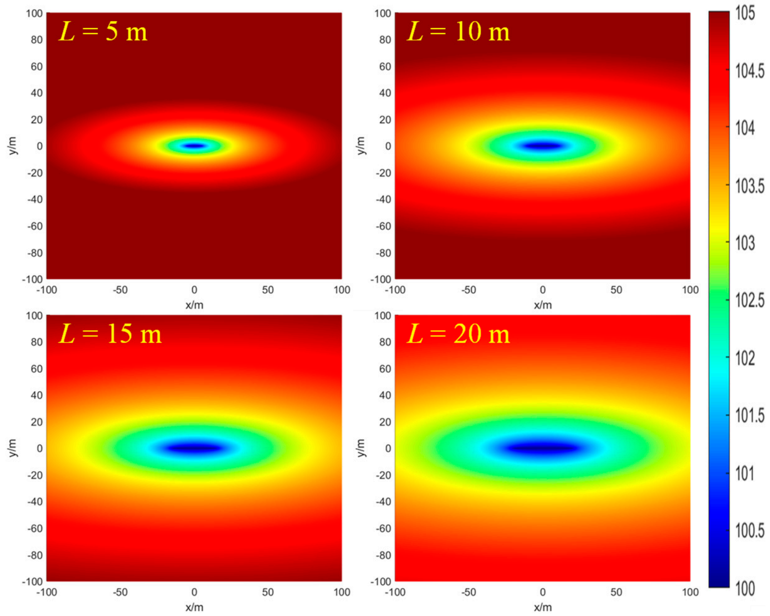


Figure 6. Distribution of pressure field of fractured coal seam under heterogeneous state.

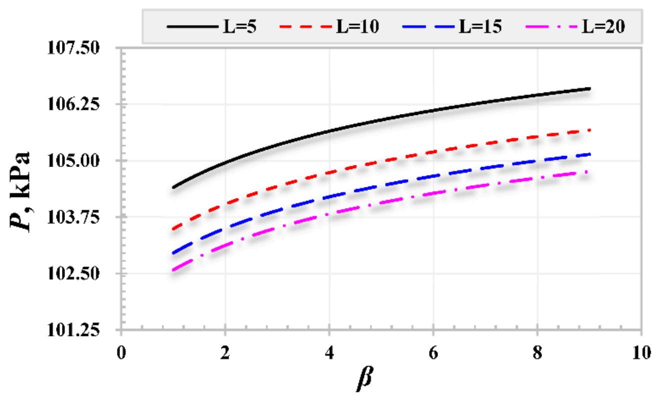


Figure 7. Pressure drop law of coal seam in a single borehole heterogeneous fracturing reservoir.

In Figure 7, it can also be concluded that if the half length of fracturing is set to be equal to 10 m, the influence of heterogeneity change on the coal seam pressure field can be studied (i.e., $\beta = 2$, $\beta = 4$, $\beta = 6$, $\beta = 8$). With the increase in the anisotropy coefficient, the average value of CBM pressure increases gradually. The coal seam pressure drop diagram is shown in Figure 8. With the increase in the anisotropy coefficient, the pressure drop area becomes smaller and smaller, and the elliptical distribution tends to be flattened. After calculation, the average pressure increases from 104.04 kPa, when the anisotropy coefficient is equal to 2, to 105.53 kPa, when the anisotropy coefficient is equal to 8, and the pressure drop effect decreases significantly.

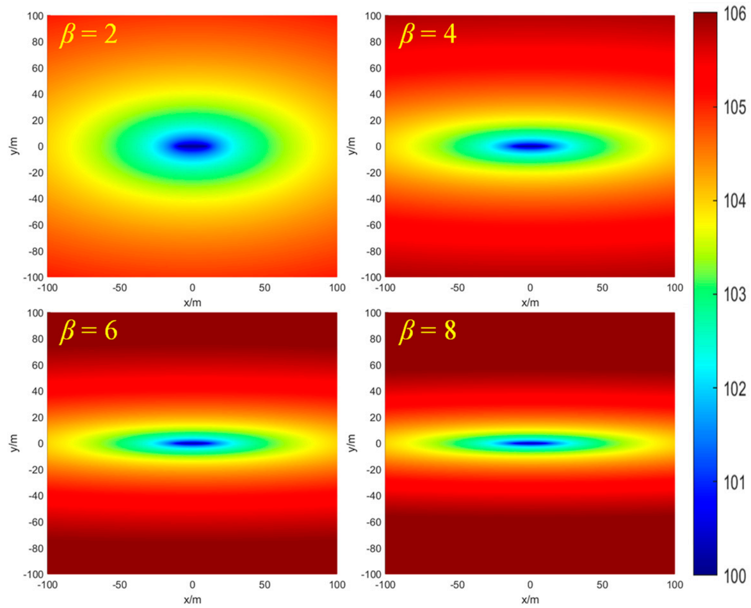


Figure 8. Pressure field distribution of heterogeneous coal seam under fracturing.

3.4. Impact of Fracturing Length for a Multi-Well Production Case in a Homogeneous Coal Seam

Continuing the research on the flow field dynamics of a single borehole unfractured homogeneous coal seam, in the extraction of an unfractured homogeneous coal seam, based on the principle of disturbance superposition, the coal seam pressure field of each single borehole is superimposed to form the distribution of the coal seam pressure field of a multi-well case. This study takes the analysis of four holes as an example, as shown in Figure 9. Based on the visual superposition of a single borehole CBM pressure into a multi-well CBM force field visualization, Figure 9a shows that the multi-well CBM pressure is evenly distributed around the borehole, and its pressure drops in the X and Y directions are equal, showing the homogeneous pressure drop characteristics during CBM extraction. Figure 9b shows the distribution of coal seam pressure force field during coal seam fracturing in the homogeneous state. The half-length of coal seam fracturing is 10 m. It can be seen from the figure that around the fracturing of four wells, the pressure drop in the X direction is greater than that in the Y direction. According to the results shown in Figure 9b, the pressure drop area is significantly larger than that in Figure 9a, and this can be found by comparison with the color between the four wells: the blue area of Figure 9b is larger than that of Figure 9a. Therefore, the centralized extraction of CBM by multi-well production and the fracturing of the coal seam are more conducive to the extraction of CBM. This result has important reference significance for the field gas pressure analysis and guiding the efficient exploitation of CBM.

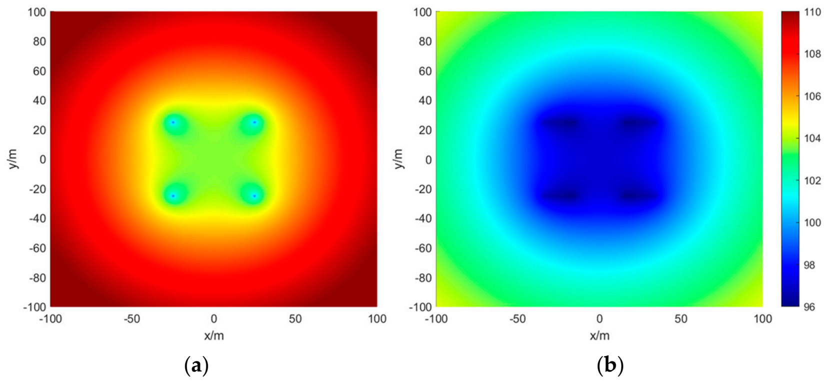


Figure 9. Distribution of pressure field in multi borehole coal seam under homogeneous state: (**a**) Unfractured coal seam, (**b**) Coal seam fracturing.

Research on flow field dynamics during continuous fracturing of a single borehole pumping a homogeneous coal seam is shown next. In fracturing homogeneous coal seam pumping, based on the principle of disturbance superposition, the coal seam pressure field of each single borehole is superimposed to form the distribution of the coal seam pressure field of multiple holes. According to the superposition principle of the pressure field, the pressure field is superimposed for different fracturing half-lengths (i.e., L = 5 m, L = 10 m, L = 15 m, L = 20 m). The superposition results are shown in Figure 10. During CBM extraction, the CBM pressure in the multi-well case is unevenly distributed around the boreholes, and the pressures in the X and Y directions are significantly different. In addition, as the half-length of the fracture changes from 5 m to 20 m, the pressure drop effect of the CBM pressure between the four boreholes is more obvious, and the pressure drop effect in the X direction becomes better and better in the process of fracture increase. The average pressure drop of the four coal-bed gas samples calculated by MATLAB is between 97.89 kPa and 96.21 kPa, as shown in Figure 10. It can be seen in Figure 11 that the pressure of CBM also decreases with the increase in the fracture half-length in the case of multi-well pumping under a homogeneous unfractured state. Therefore, we can draw a conclusion that increasing the half-length of coal seam fracturing can obtain a good pressure drop effect around the borehole when extracting coalbed methane from a homogeneous coal seam with multiple wells. Therefore, the extraction efficiency of coalbed methane can be better improved.

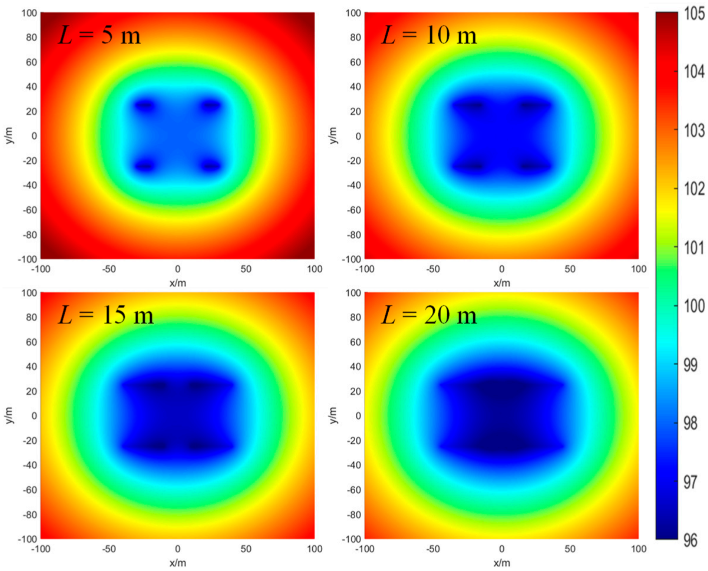


Figure 10. Distribution of pressure field of coal seam under homogeneous fracturing.

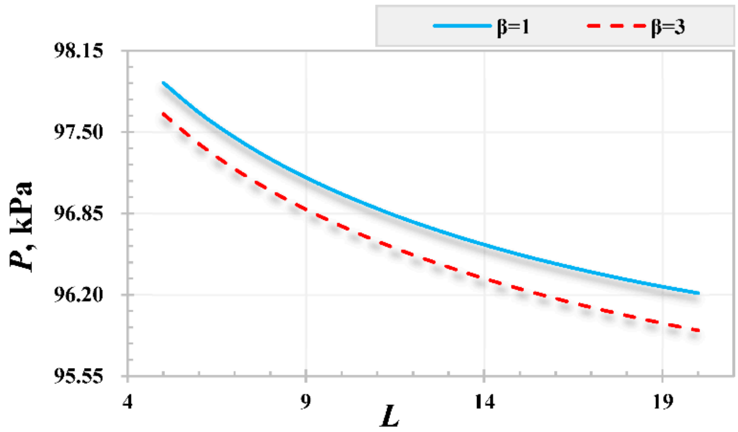


Figure 11. Pressure drop law of coal seam in multi-well fracturing reservoir.

3.5. Impact of Anisotropy under the Condition of Multi-Well Production without Fracturing

Similar to the study under the condition of multi-well fracturing homogenization, the influence of the change in the anisotropy coefficient on the coal seam pressure drop is compared under the condition of multi-well fracturing, and the results are shown in Figure 12. The anisotropy coefficients are equal to 2, 4, 6, and 8. It can be observed from Figure 12 that the CBM pressure in the X direction of the superimposed CBM pressure field is significantly smaller than that in the Y direction. With the change in anisotropy coefficient from 2 to 8, the uneven distribution of pressure in the X and Y directions is more obvious, the pressure drop range in the X direction is larger, and the pressure drop range in the Y direction is smaller. We can conclude that when extracting coalbed methane without fracturing in multiple wells, the existence of coal seam heterogeneity can affect the pressure drop around the borehole, and with the increase in coal seam heterogeneity, the pressure drop effect around the borehole becomes better and better. Therefore, the extraction efficiency of coalbed methane can be better improved.

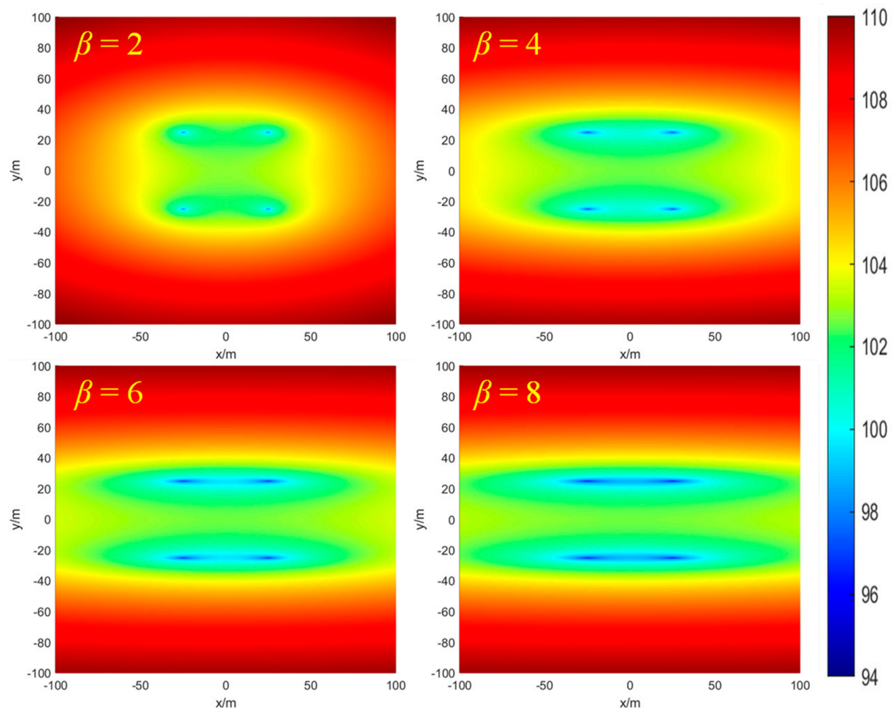


Figure 12. Distribution of pressure field of coal seam under homogeneous state without fracturing.

3.6. Impact of Anisotropy under the Condition of Multi-Well Production with Fracturing

It is also similar to the study under the homogeneous condition of multi borehole fracturing. However, in this study, the influence of heterogeneity and fracturing on the pressure field of the coal seam is comprehensively considered. The anisotropy coefficient is set to 3, and then the half-length of the fracturing is adjusted to carry out the data visualization study of the coal seam pressure force field, in which the half-lengths of the fracturing are 5 m, 10 m, 15 m, and 20 m. As shown in Figure 13, based on the superposition of a single borehole CBM pressure visualization into multi-borehole CBM force field visualization, it can be seen that under the joint action of coal seam heterogeneity and drilling fracturing fractures, the pressure reduction effect around the four wells is more obvious, and the pressure drop range is wider than that when the coal seam heterogeneity or drilling fractures act alone. Due to the half-length and heterogeneity of fractures, the pressure of the CBM in multiple wells is unevenly distributed around the boreholes, and the pressure in X and Y directions is significantly different. In addition, as the half-length of the fracture changes from 5 m to 20 m, the pressure drop effect of the CBM pressure between the four boreholes is more obvious. As shown in Figure 13, however, during the increase in the fracture half-length, the coal seam pressure force between the four boreholes decreases from 97.64 kPa to 95.92 kPa, the pressure drop effect in the X direction becomes better and better, and the pressure drop effect in the Y direction is less and less obvious, showing the influence of coal seam heterogeneity and fracture half-length on the borehole layout mode. The relationship between the pressure of the four boreholes and the half-length of the fracture is shown in Figure 11. It can be seen that with the increase in the half-length of the fracture, the CBM pressure gradually decreases, which can effectively improve the extraction efficiency of CBM. The research of this content has reference significance for the optimization of drilling work.

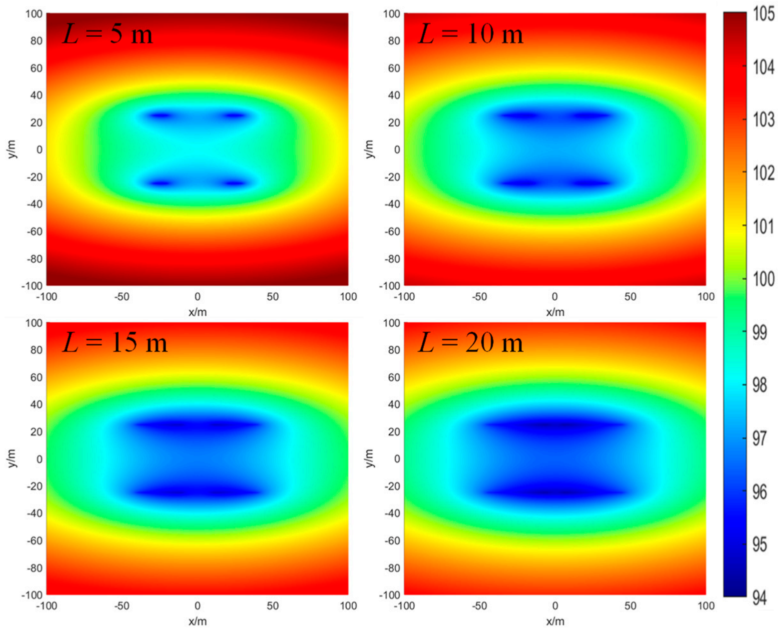


Figure 13. Pressure field distribution of coal seam under heterogeneous fracturing.

4. Conclusions

(1) In the study of the pressure field distribution of a coal seam in a single borehole, under the condition of a constant anisotropy coefficient, fracturing can effectively reduce the pressure around the borehole and has a good pressure drop effect. In addition, the greater the half-length of the fracture, the better the effect of the coal seam's pressure drop. When the fracture half-length is certain, heterogeneity can

affect the CBM pressure around the borehole. With the increase in the anisotropy coefficient, the CBM pressure increases gradually.

(2) In the homogeneous fractured coal seam with multiple wells, the pressure effect under the joint action of multiple wells is the same as that of a single borehole. Under the condition of constant homogeneity, with the increase in the fracturing half-length, the pressure of CBM decreases gradually, which has a good pressure drop effect and is more conducive to the extraction of CBM. In the multi-well heterogeneous fracturing coal seam, under the condition of constant heterogeneity, with the increase in fracturing half-length, the coal seam gas pressure gradually decreases, which has a good pressure drop effect and is more conducive to the extraction of coal seam gas.

(3) The pressure distribution between the four wells shows significant non-uniformity in the multi-well CBM extraction. Therefore, there is an optimal hole layout mode to minimize the average pressure between the four wells and achieve better pumping effect.

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