An explanation of large-scale coal and gas outbursts in underground coal mines: the effect of low-permeability zones on abnormally abundant gas

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Abstract

Large-scale coal and gas outbursts pose a risk of fatal disasters in underground mines. Large-scale outbursts (outburst of coal and rock greater than 500 t) in recent years in China indicate that there is abundant gas in areas of outbursts containing large amounts of potential energy. The adequate sealing properties of the roof and floor of a coal seam are required for local abundant gas around the site of an outburst, but an annular low-permeability zone in a coal seam, which prevents the loss by gas migration through the coal seam itself, is also required. The distribution of coal gas with this annular zone of low permeability is described, and it is proposed that the annular zone of low permeability creates conditions for confining the coal gas. The effect of this low-permeability zone on the gas distribution is analyzed after allowing for simplifications in the model. The results show that the permeability and length of the low-permeability zone have a great impact on the gas distribution, and the permeability is requied to be several orders of magnitude less than that of normal coal and enough length is also in demand. A steep gradient of gas pressure in the low-permeability zone and the high gas pressure in the abundant zone of gas can promote coal mass failure and coal wall deformation, thereby accelerating the coal and gas outburst. The high pressure gas in abundant zone of gas will lead to a large-scale outburst if an outburst occurs.

1 Introduction

Coal and gas outbursts are a form of dynamic failure in which coal and gas are ejected violently by coal gas which is generated and stored in the coal. These outbursts are a concern for mine safety worldwide (Lama and Bodziony, 1998; Beamish and Crosdale, 1998). The largest of these outbursts, which may involve more than 500 tons of coal and rock, fill the working face or roadway with large volumes of coal, destroy roadway facilities by the sudden outflow of gas and even ruin an entire ventilation system. In such cases, even underground mine workers far from the site of the outburst may be affected, causing massive casualties.

In coal and gas outbursts prevention, regional gas control technologies, such as protecting seam exploitation, pressure-relief gas extraction, and strengthening gas extraction in advance, are the main technical approaches in China (Cheng and Yu, 2007). Protecting seam exploitation is the preferred approch for coal seam group. For efficient resource utilization and atmospheric environment protection, co-extraction of coal and methane has become a widely accepted idea in recent years(Guo et al., 2012). Underground boreholes and surface vertical wells are extensively utilized in gas drainage(Sang et al., 2010;Ying-Ke et al., 2011;Yang et al., 2011). Waterjet(Lu et al., 2011), hydraulic fracturing(Huang et al., 2011) and water infusion(Díaz Aguado and González Nicieza, 2007) are also used to reduce the risk of coal and gas outbursts. The development of coal and gas outbursts prevention benefits from the advance in outburst mechanism and the deeper reognization is still in demand.

Coal and gas outbursts are a complex process involving gas migration, coal failure and their interaction. Currently, a model synthesizing stress, coal gas, and coal physical and mechanical properties is widely used in qualitative descriptions of outburst conditions and processes. To quantitatively explain these outbursts, models describing coal mass failures caused by stress and coal gas have been developed after simplifying the physical processes involved (Paterson, 1986; Choi and Wold, 2001; Xu et al., 2006; Xue et al., 2011). Other related studies have analyzed the outburst conditions with regard to the tectonic conditions (Cao et al., 2001), spatial variability of permeability (Wold et al., 2008), and in situ stress characteristics (Han et al., 2012).

The understanding of the mechanism of large-scale outbursts is based on the above results, and further research into their particular conditions is lacked. These large-scale outbursts are pernicious due to the huge amount of energy released by gas flow, and the factors affecting the distribution of the energy before the outbursts warrant further study. Based on the large-scale outbursts in China over the last several years, their abnormal abundance in coal gas was analyzed, and the effects that low-permeability zones in coal seams have on the abnormal abundance of coal gas and large-scale outbursts were studied.

2 Abnormally abundant gas and geologic structures in large-scale outbursts

2.1 Abnormal abundance of coal gas in large-scale outbursts

The study by Valliappan and Wohua (1999) showed that coal gas was primarily responsible for the energy released in the outbursts. As a result, the large-scale outbursts are accompanied by enormous amounts of outburst gas. As shown by the large-scale outbursts in China over the past few years in Table 1, and the locations are shown in Fig.1. The amount of outburst gas could be hundreds of thousands of cubic meters. The concentration increase could be detected by the gas sensores and the amount of outburst gas is estimated by the quantity difference between the amount of coal gas in the airflow during the outburst and the amount in the normal times. In other words, hundreds of cubic meters of coal gas gush out per ton of outburst coal. This outflow of coal gas measures several to dozens of times the local gas content in nearby normal coal seam and the coal gas content in the outburst area that is much more than the coal gas in other parts of the coal seam is abnormal. If these coal masses were mined normally, the gas outflow would be far less than the gas accompanying an outburst. Consider the example of the large-scale outburst in the Daping Coal Mine on the 20th of October, 2004. The outburst of coal and rock measured 1894 t (coal mass 1362 t), and the gas associated with the outburst measured approximately 250 thousand cubic meters. The coal seam Ⅱ1 was being mined. The gas emissions in this coal mine measured 11.47 m^3/t in 2003. This measurement indicates that if the outburst coal were mined normally, the accompanying gas would measure 15622 m^3, which is far below the amount of outburst gas. On the one hand, this amount indicates that the effect of stress release associated with the coal outburst is more pronounced than the stress release during normal mining. On the other hand, the amount demonstrates that the gas in and near the outburst area is more abundant than in other areas and could provide a large number of coal gas for the large-scale outbursts.

2.2 Abnormal presence of coal gas and associated geologic structures

Coal and gas outbursts tend to occur in zones affected by geological structures (Shepherd et al., 1981; Cao et al., 2001), and large-scale outbursts occur more often in or nearby the geological structures, as in the cases listed in Table 1. In tectonic regions, the coal seam is deformed by the tectonic stress, creating conditions conducive to outbursts, including reduction in coal strength and high stress. At the same time, geological structures altered the conditions for generation, storing and migration of coal gas in coal measures. The distribution of coal gas in the same coal seam may vary greatly even at the same depth. The changes in load stress and fracture systems in coal masses by geological structures (Li et al., 2003; Han et al., 2012) are one factor controlling the migration of coal gas and the consequent distribution of coal gas (Pashin, 1998; Ayers, 2002; Yao et al., 2009; Groshong, Jr,, et al., 2009; Cai et al., 2011). These changes created conditions conducive to outbursts, particularly large-scale outbursts backed by tremendous amounts of energy stored in the gas.

During work to control coal mine gas in the past years, it was found that the distribution of gas is nonuniform due to geological structure, and certain tectonic structures are beneficial to the storage of coal gas. The outbursts nearly always occurred in long, narrow ‘‘outburst zones’’ along the intensely deformed zones of geological structures (Cao et al., 2001), and the research focus in the paper is put on the mine-scale geological structures or smaller ones. In coal measures in a syncline or anticline, the amount of coal gas is relatively high in the axial zone, when the roof and floor of the coal seam display good sealing properties, as shown in Fig. 2 (a, b). Faults sealing constitute a low-permeability boundary and block the migration of coal gas, and abnormally abundant gas often develop next to these fault contacts, as shown in Fig. 2 (c). In cases in which the coal seam thickness is altered by tectogenesis, a coal seam thickens in a local area, producing a coal package. The surrounding area of the coal seam thins, and the migration of coal gas becomes more difficult, leading to the sealing of coal gas in the package, as shown in Fig. 2 (d). These areas are also associated with large-scale outbursts, as listed in Table 1.

3 Modeling and analysis of abundant gas preservation

3.1 Preservation conditions of abundant gas and annular zone of low permeability

Enormous amounts of outburst gas indicate that abnormally abundant coal gas has been stored in the outburst area, which is indicative of the large amount of energy required for a large-scale outburst. In addition to the good sealing properties of roof, the area surrounding the abundant gas zone in the coal seam should be low permeability to impede the loss of high pressure gas through the coal seam itself. Such a zone of concentrated coal gas held within an annular zone of low permeability is shown in Fig. 3 and the spatial scale is about mine-scale. This zone of low permeability confines the concentrated coal gas zone and maintains the gas content at a level higher than that of normal areas of the coal seam throughout a certain span of time. In areas of tectonism, the alteration of the fracture system in the coal seam reduces the permeability greatly (Li et al., 2003), and the high tectonic stress can decrease the permeability greatly as well (Somerton et al., 1975; Jasinge et al., 2011). A low-permeability zone can develop and affect the coal gas distribution, i.e., the preservation conditions resulting in abnormal concentrations of coal gas and the consequent energy for large-scale outbursts.

To analyze the effect that low-permeability zones in coal seams exert in coal gas preservation, it was assumed that the coal gas migration does not involve continuing gas generation nor boundary changes by geological structure that might affect gas migration. With their effective sealing properties, the roof and floor of the coal seam are regarded as non-flow boundaries. Given the above simplifications, a concentration of coal gas within an annular zone of low permeability can be simplified as a one-dimensional flow model involving porous media.

The continuity equation of gas migration in the coal seam can be expressed as

$$\frac{\partial(m)}{\partial t}-\nabla\cdot\left(\rho_g v_g\right)=0, \tag{1}$$

where m is the coal gas content (kg/m^3), ρ_g is the coal gas density (kg/m^3), V_g is the seepage velocity (m/s) and t is time (s). The coal gas consists of adsorbed gas and free gas, and the content can be calculated using

$$m=\left(\frac{V_L p}{p+p_L}+\frac{\phi p}{\rho_c p_0}\right)\cdot\frac{\rho_c M}{V_M}, \tag{2}$$

where V_L is the maximum adsorption capacity of the coal mass (m^3/t), p_L is the Langmuir pressure representing the increasing trend of the adsorption volume with the gas pressure (MPa^{-1}), p is the coal gas pressure (MPa), ρ_c is the bulk density of coal (kg/m^3), ϕ represent the porosity of coal and p_0 is the atmospheric pressure 0.10325 MPa. The coal gas density can be calculated using the ideal gas equation

$$\rho_g = \frac{pM}{RT}, \tag{3}$$

where M is the molar mass of the gas (16 g/mol for methane), R is the gas constant 8.314 J/(mol·K) and T is the coal seam temperature (K).

The coal gas migration in the coal seam is flow that obeys Darcy's law, given as

$$V_g = -\frac{k}{\eta_g}\nabla p. \tag{4}$$

where η_g is the coefficient of kinetic viscosity (1.08×10^{-5} pa·s for methane) and k is the permeability of the coal seam (m^2).

The model for analyzing the preservation effect on coal gas is a one-dimensional flow model with a low-permeability zone, as shown in Fig. 4. The total length is 2500 m, and the zone Ⅰ is 100 m wide. The permeability of zones Ⅰ and Ⅲ are those of a normal coal seam, and zone Ⅱ is a low-permeability zone. The parameters of the model are shown in Table 2. The initial gas pressure in the coal seam is 2.5 MPa. The right boundary is a low-pressure boundary, and the pressure is atmospheric. Because the coal gas in the zone inside the annular low-permeability zone is limited, the left boundary is considered a non-flow boundary.

3.2 Results and analysis

Based on a length of zone Ⅱ of 200 m, cases in which the permeability was 10%, 1%, 0.1% and 0.01% of the permeability of a normal coal seam were analyzed. After various times of gas migration, the gas pressure distributions from the left boundary are shown in Fig. 5. From these calculations, we found that the gas lost through the coal seam is reduced by the low-permeability zone. When the permeability of zone Ⅱ was smaller than 0.1% of the permeability of the normal coal seam, the gas in zone Ⅰ can still maintain the initial gas pressure (2.5 MPa) even after 10^4 years. The coal gas in zone Ⅰ can maintain high pressure after a long period of gas migration. In the numerical example the gas pressure in zone Ⅰ with coordinate less than 100m, which is inside the low-permeability zone with 0.01%, can be 1.69 MPa after 10^6 years of gas migration, much higher than 0.15 MPa in the case without low-permeability zone. Due to the permeability reduction of the low-permeability zone, the abundant gas zone can maintain higher gas pressure, resulting in an abundant zone of gas.

And the gas pressure gradient steepens as well. The concentration of coal gas outside the zone is less than that of a normal coal seam due to insufficient replenishment from the low-permeability zone. The gas pressure in the case of 0.01% permeability in zone Ⅱ was 1.38 MPa at position of 300m after 10^4 years of gas migration, lower than 1.50MPa in the case without low-permeability zone. But this effect would vanish as the time. When the coal seam contains no low-permeability zone or its permeability is merely several times less than the normal permeability, the coal gas will escape though low-pressure boundaries around the coal seam. No local concentration of gas can develop, even though the roof and floor strata exhibit good sealing properties.

The effect of the width of the low-permeability zone in cases where the permeability of the low-permeability zone is 0.1% of the normal coal seam permeability was studied. The gas pressure distributions are shown in Fig. 6, in which the length of the low-permeability zone was 2 m, 20 m, 200 m and 2000 m. The results demonstrate that the length of the low-permeability zone has an important effect on gas preservation. In the example, when the length of the low-permeability zone was 2000m the the gas pressure in the zone with coordinate less than 100m can be still more than 2.4MPa after 10^5 or 10^6 years, much higher than other cases. The larger low-permeability zone promotes the confinement of the coal gas, and this effect becomes more pronounced with time. A narrower low-permeability zone may create a larger gas pressure gradient.

Based on the above analysis, we conclude that when a low-permeability zone is present in a coal seam, a high gas pressure gradient is present in this zone, and the coal gas can be held in the inner zone, thus creating a local abundant zone of gas during the long time gas migration. In this process, to maintain the coal gas in the the inner zone, the permeability of the low-permeability zone is requied to be several orders of magnitude less than that of normal coal and the length is also in demand.

4 Effect of low-permeability zone on the likelihood of outburst

4.1 Model and conditions

A higher gas pressure gradient increases the likelihood of an outburst (Williams and Weissmann, 1995). A high gas pressure gradient and high gas concentrations tend to be associated with low-permeability zones. In this section of the paper, a model for analyzing the effect that low-permeability zones have on producing outbursts is described.

Considering the effect of coal gas pressure on the stress state, the effective stress in the coal mass can be expressed as

$$\sigma_{ij} = \sigma_{ij}^{'} - \delta_{ij} \alpha p \, , \tag{5}$$

where σ_{ij} is stress, $\sigma_{ij}^{'}$ is the effective stress, δ_{ij} is the Kronecker delta function which is 1 when i=j, and α is the pore pressure coefficient.

In this model, the coal mass is regarded as an elastic-plastic medium, following the Mohr-Coulomb matching Drucker-Prager yield criterion

$$F = \alpha_{DP} I_1 + k_{DP} - \sqrt{J_2} \, , \tag{6}$$

where I_1 is the first stress invariant, J_2 is the second deviator stress invariant, and α_{DP} and k_{DP} are identified by the cohesion C and friction angle φ as

$$\alpha_{DP} = \frac{\sin\varphi}{\sqrt{3}\sqrt{3 + \sin^2\varphi}} \, , \tag{7}$$

$$k_{DP} = \frac{3C\cos\varphi}{\sqrt{3}\sqrt{3 + \sin^2\varphi}} \, . \tag{8}$$

The mechanical parameters in the model are listed in Table 3, and the geometry and boundary conditions are shown in Fig. 7. The roof and floor strata are impermeable, and the roof is loaded by 400 m of overlying rock. The permeability values of the low-permeability zone are 10%, 1%, 0.1% and 0.01% of normal coal seam permeability, and the low-permeability zone is 20 m long. The initial gas pressure is 2.5 MPa, and the migration conditions are the same as those in the above analysis of the effect of the low-permeability zone on gas migration. After the coal gas migration, for 10^5 years in this study, the gas distribution is different. A coal mass 5 m long in the front of low-permeability zone is excavated, and the plastic development in front of coal wall and the deformation of coal wall are analyzed.

4.2 Results and analysis

After 10^5 years of gas migration, the gas pressure distributions in the coal seam with various low-permeability zones progressing away from the left boundary are shown in Fig. 8. The gas pressure outside the low-permeability zone is close to that of the normal coal seam and is progressively higher in the low-permeability zone. The gas pressure at position 100m was 1.47MPa, 0.74MPa, 0.59MPa, 0.57MPa, 0.57MPa as the permeability reduction of low-permeability zone. Then, the 5-m-long coal mass in the front of low-permeability zone, shown by the gray area in Fig. 8, is excavated. The effect of the concentrated gas and the pressure gradient with the various low-permeability zones on the deformation and failure of the coal mass is studied.

The area of plastic failure and maximum plastic strain of the coal mass in front of the coal wall are more severe with a low-permeability zone and become more pronounced with the permeability decrease in the low-permeability zone, as shown in Fig. 9. The coal wall in front of the low-permeability zone displays greater deformation as well. As shown in Fig. 10, the maximum strain and displacement of the coal wall are progressively larger with the progressive decrease in permeability in the low-permeability zone. These effects are especially pronounced when the permeability of the low-permeability zone is very low. These findings demonstrate that with greater pressure gradient the low-permeability zone has a significant impact on the likelihood of outbursts.

The failure of the coal mass and deformation of the coal wall are promoted by the high gas content and gas pressure gradient created by the low-permeability zone, which initiates and accelerates the outbursts. The high energy of the coal gas in the abundant zone of gas provides the enormous amounts of energy released in outbursts in general and large-scale outbursts in particular. Even where a coal seam contains little gas and the outburst danger is generally low, local large-scale outbursts at that same depth are possible due to the gas contained within low-permeability zones. More prevention measures are required in such areas than in normal coal seams.

5 Conclusions

The analysis of large-scale outbursts in recent years in China indicates that there are abundant zones of gas near outburst locations. Large-scale outbursts are common in areas affected by geological structures, which reduce the permeability of coal through deforming fracture systems and the high stress state. The resulting lower permeability zones can alter the distribution of gas, and form zones of abundant gas over long periods of time associated with gas migration.

Besides good sealing properties of the roof and floor rocks, the local abundant gas at the site of an outburst requires a low-permeability zone in the coal seam to prevent the migration and loss of gas through the coal seam itself. The distribution of abundant coal gas inside an annular zone of low permeability is proposed, and the effect of the low-permeability zone on gas distribution is analyzed based on simplifications. The results indicate that the gas inside a low-permeability zone can be contained over a long span of time, leading to local pockets of concentrated gas. Without the effect of low-permeability zones, the high pressure gas would be lost across the low-pressure boundaries of coal seam. In the long time of gas migration, to maintain the coal gas in the the inner zone, the permeability of the low-permeability zone is requied to be several orders of magnitude less than that of normal coal and enough length is also in demand.

The steep gradient of gas pressures in a low-permeability zone and high-pressure gas in the abundant zone of gas may create conditions conducive to coal and gas outbursts even if it is safe in surrounding area. When excavation proceeds into the low-permeability zone, the failure of the coal mass and deformation of the coal wall increase and become more pronounced with the permeability reduction of the low-permeability zone. Where high-pressure gas is confined within a low-permeability zone, large amounts of energy in the zone of abnormally abundant gas may lead to a large-scale outburst.

Acknowledgements

This work is financially supported by the National Foundation of China (No. 51074160), the National Basic Research Program of China (973 Program, No. 2011CB201204) and the National Science Foundation of China (No.51004106, No. 41202118).

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Table 1. Recent large-scale outbursts in coal mines in China

Date	Location	Quantity of outburst coal (ton)	Quantity of outburst gas (10^3 m^3)	Outburst gas per ton of outburst coal (m^3t^{-1})	Tectonic conditions	Relative gas emission rate of the entire mine (m^3t^{-1}) *
2004.08	Hongling Coal Mine in Liaoning Province	701	66.2	94.5	Fault	39.3 (2003)
2004.10	Daping Coal Mine in Zhengzhou City	1362	250	183.6	Reverse fault	11.47 (2003)
2009.11	Xinxing Coal Mine in Heilongjiang Province	1697	166.3	98.0	Normal fault, igneous rock intrusion	7.98 (2009)
2010.10	The Fourth Coal Mine of Pingyu Coal and Electricity in Henan Province	2547	150	58.9	Coal seam thickness increase	6.03 (2010)
2011.10	Jiulishan Coal Mine in Henan	2893	291.1	100.6	Reverse fault	24.17 (2010)

	Province				
2012.11	Xiangshui Coal Mine in Guizhou Province	490	45	91.8	Coal seam thickness increase
2013.03	Machang Coal Mine in Guizhou Province	2051	352	171.6	Fold and fault

*The year in parentheses is that in which the emission rate was measured.

Table 2. Parameters of the flow model

Parameter	Value	Unit
Maximum adsorption capacity of coal mass V_L	20	m^3 t^{-1}
Langmuir pressure P_L	1	MPa^{-1}
Bulk density of coal ρ_c	1.35	t m^{-3}
Porosity of coal φ	0.06	-
Coal seam temperature T	303	K
Permeability of coal seam k	0.025	mD

Table 3. Parameters used in the model

Parameter	Value	Unit
Pore pressure coefficient α	0.75	1
Cohesion of coal C_c	1.5	MPa
Friction angle of coal ψ_c	35	°
Poisson ratio of coal υ_c	0.4	1
Elastic modulus of coal E_c	2.5	GPa
Bulk density of rock ρ_r	2.5	t m^{-3}
Cohesion of rock C_r	20	MPa
Friction angle of rock ψ_r	40	°
Poisson ratio of rock υ_r	0.3	1
Elastic modulus of coal E_r	30	GPa

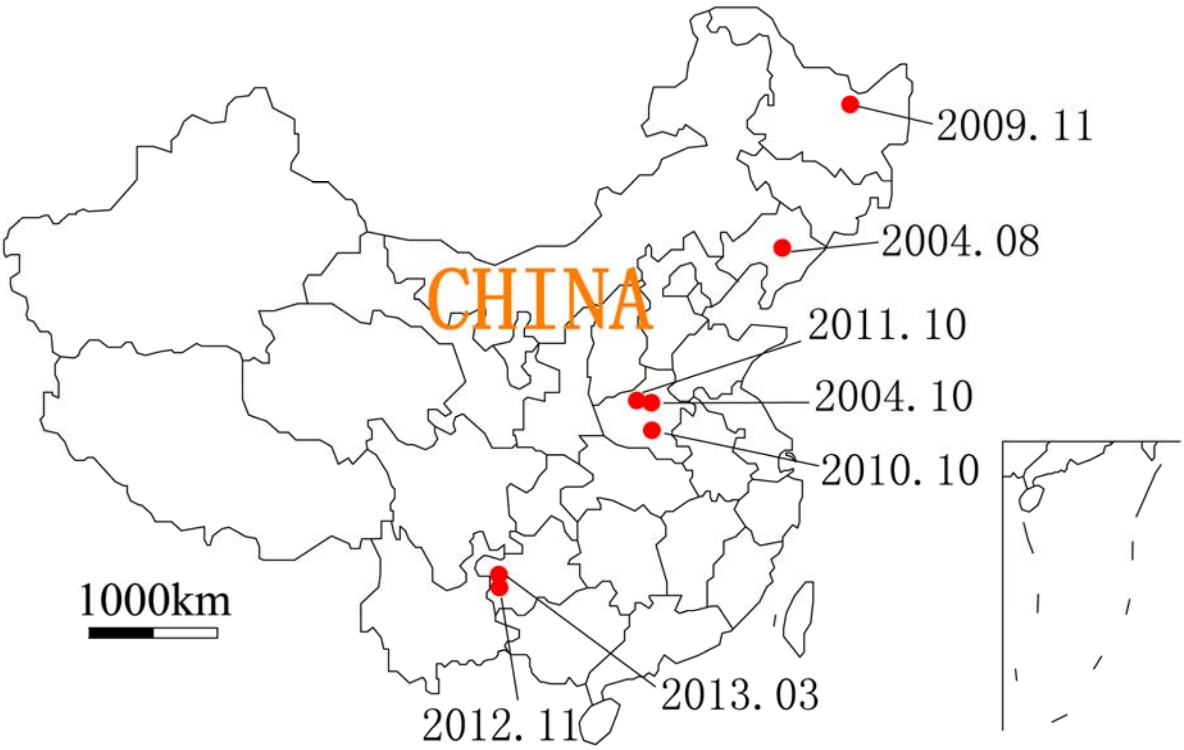

Figure 1. Locations of recent large-scale outbursts in China.

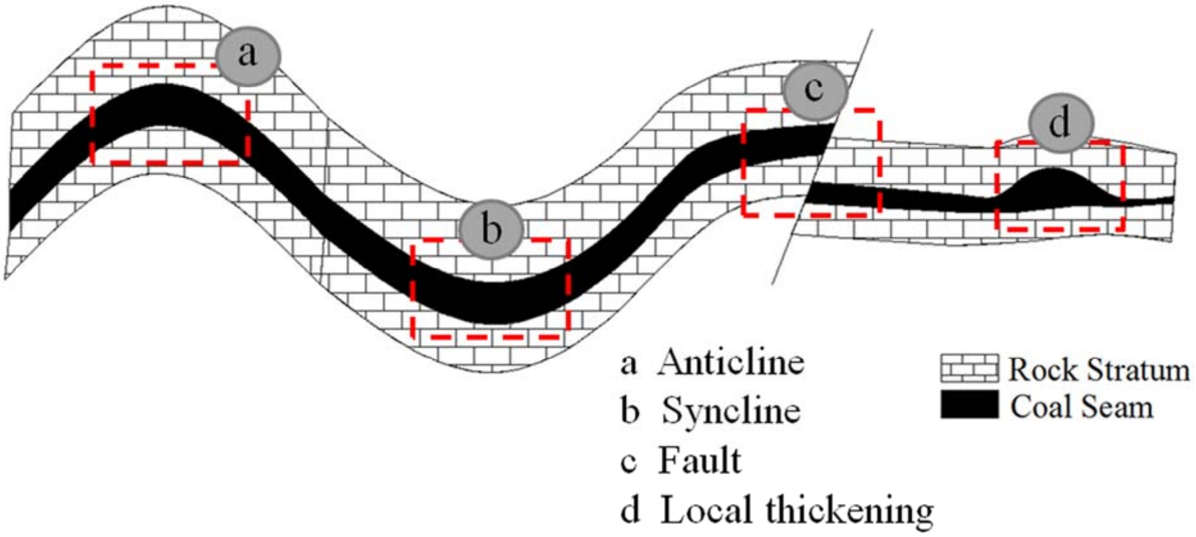

Figure 2. Abundant zones of coal gas in some geologic structures.

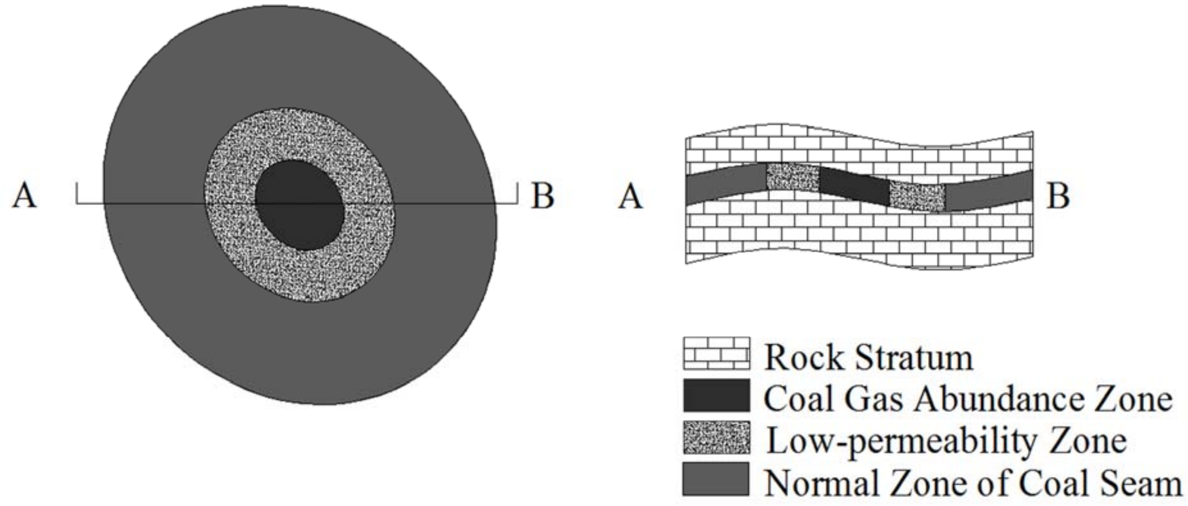

Figure 3. Annular low-permeability zone in coal seam.

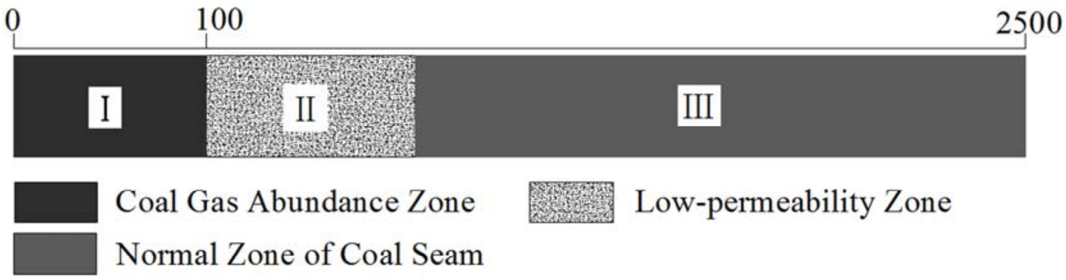

Figure 4. One-dimensional flow model of coal gas with a low-permeability zone.

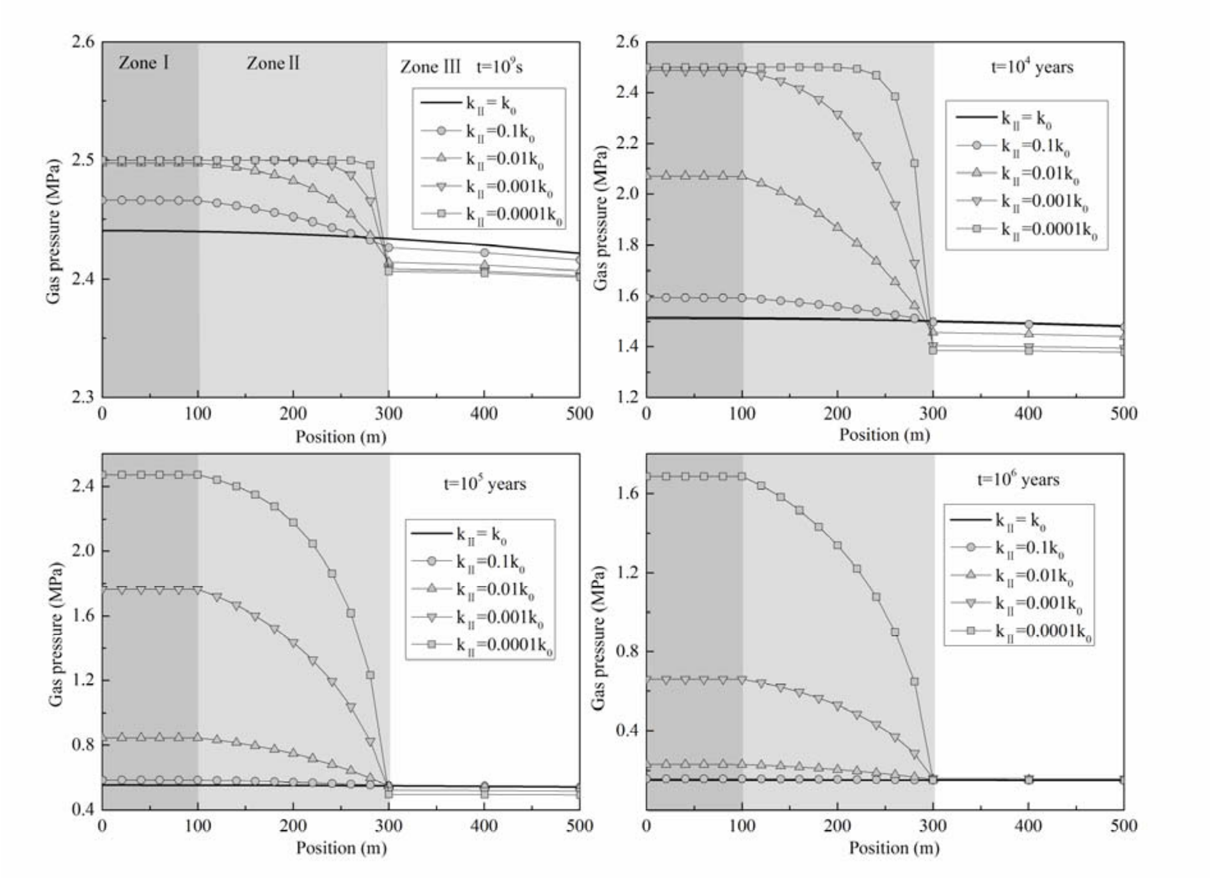

Figure 5. Gas distributions with various permeability properties of the low-permeability zone.

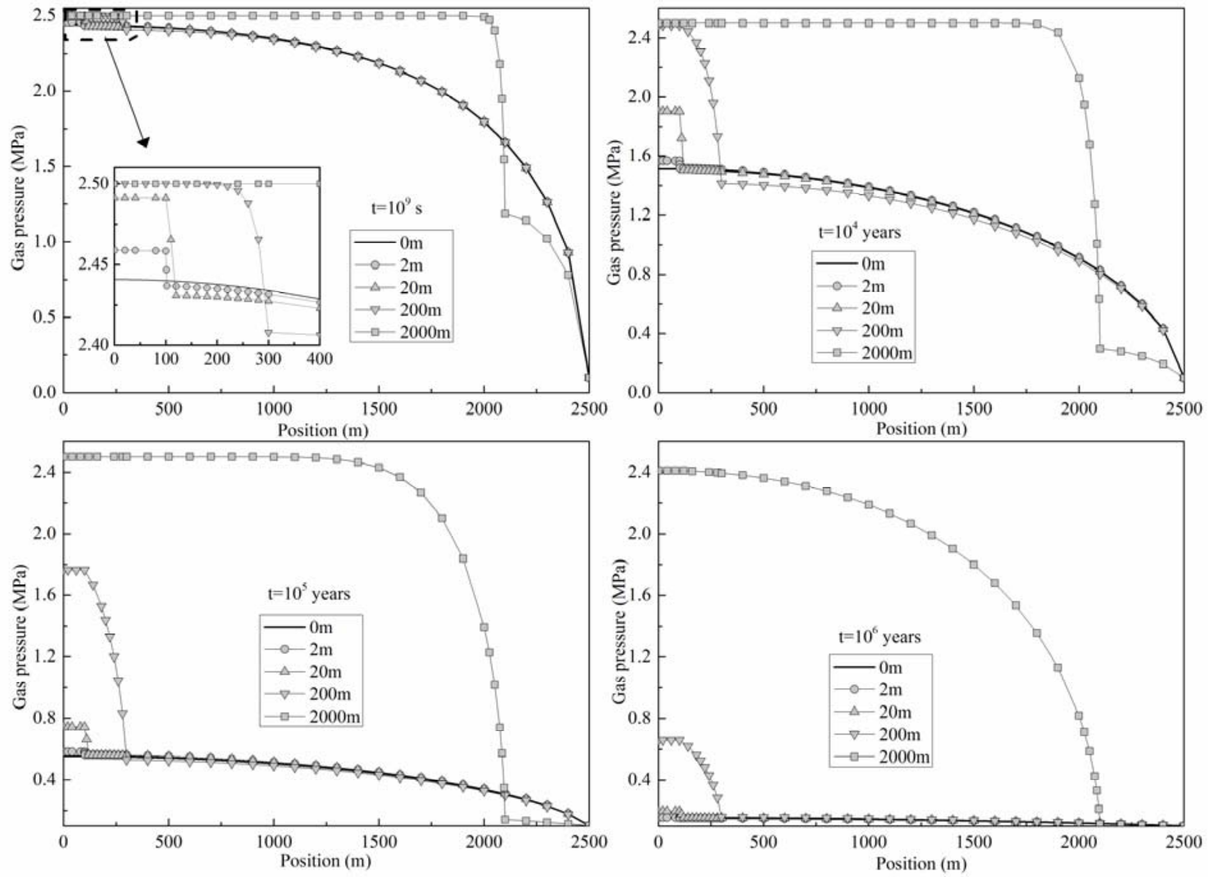

Figure 6. Gas distribution with various lengths of the low-permeability zone with permeability 0.1% of the normal coal seam permeability.

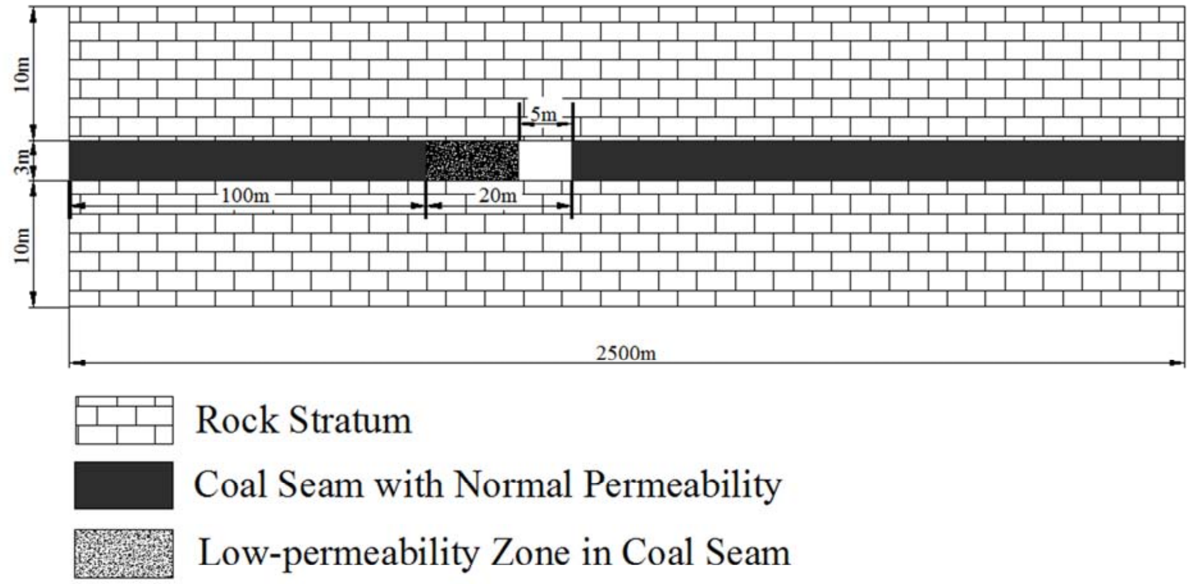

Figure 7. Geometry and boundary conditions.

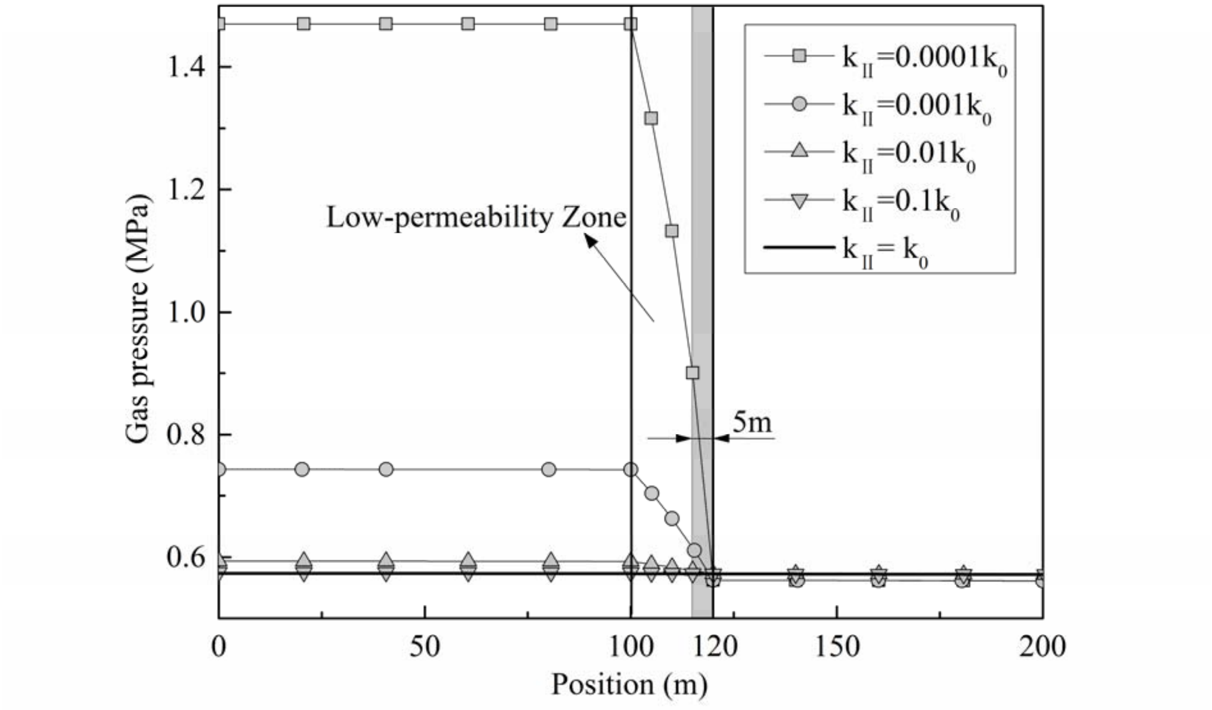

Figure 8. Gas distribution after 10^5 years of gas migration.

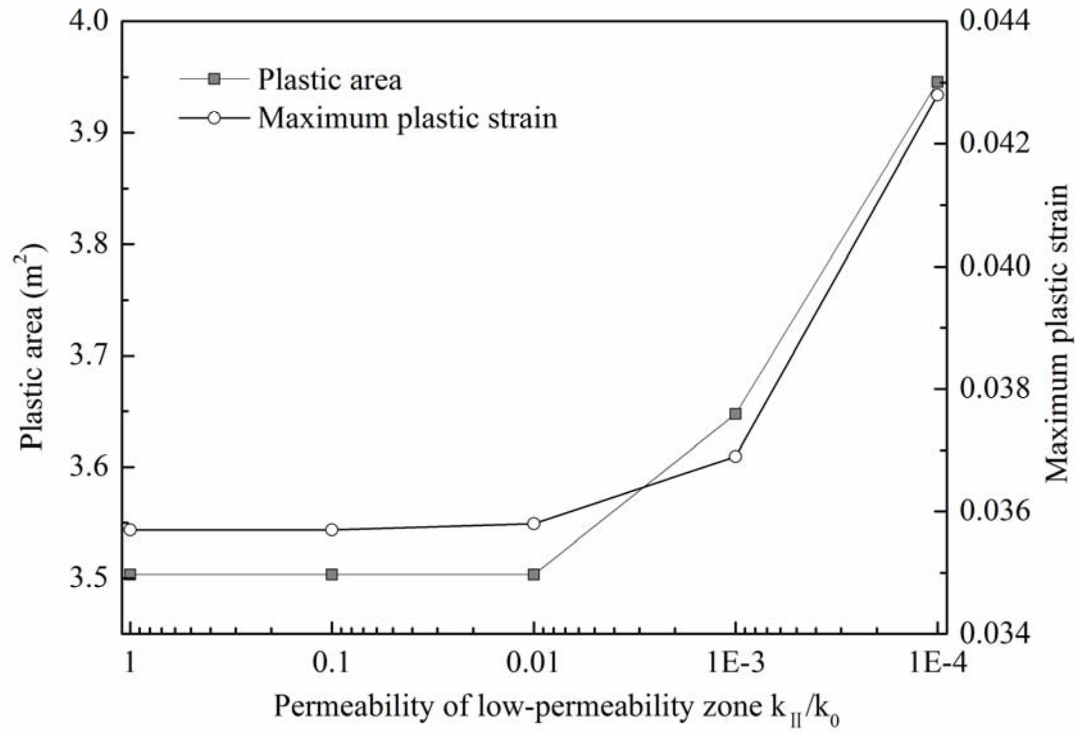

Figure 9. Plastic development in front of coal wall.

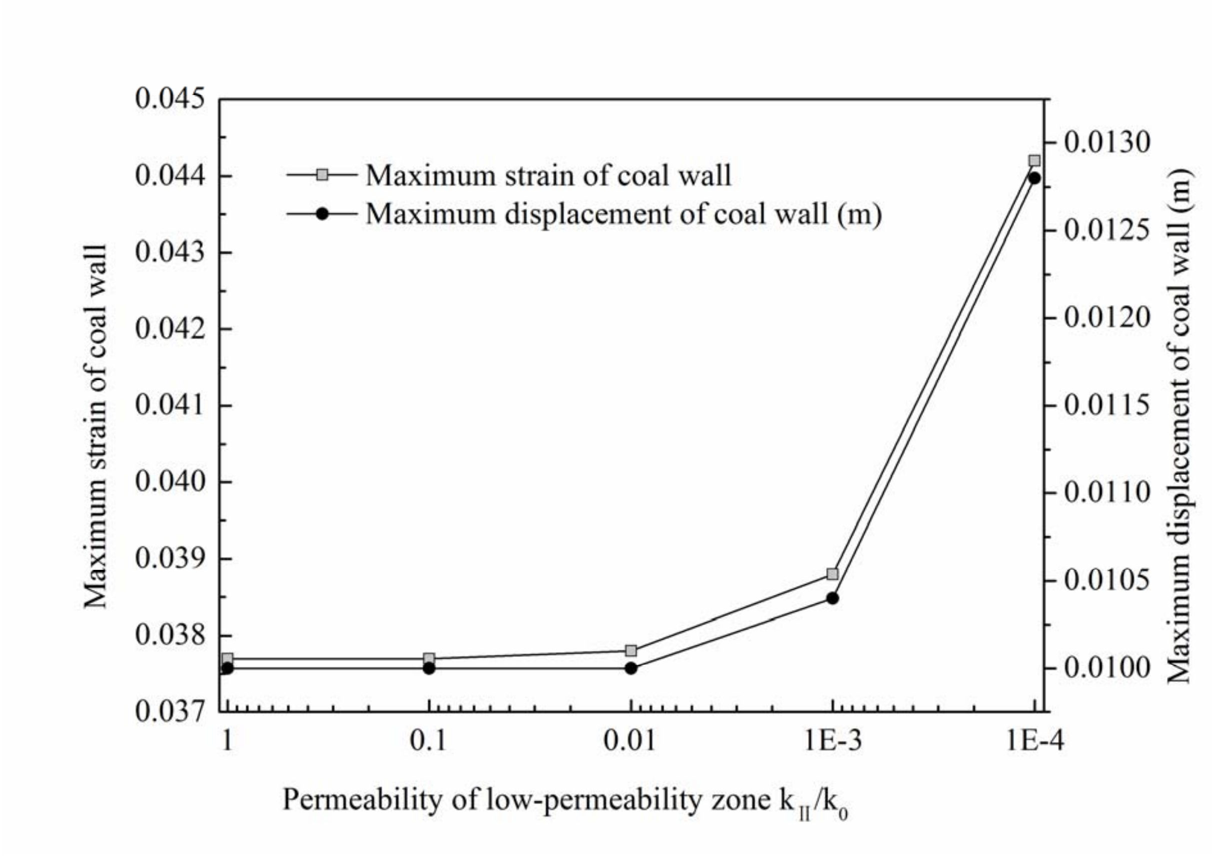

Figure 10. Deformation of coal wall.