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The laws of gas-solid coupling of coal-bed gas in deep high gassy coal seams

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ABSTRACT
In order to analyze the laws of gas-solid coupling of coal-bed gas in deep high gassy coal seams as well as to prevent the gas compound dynamic catastrophes of deep gas-filled coal-rock, a gas-solid coupling theoretical model under the influence of ground stress, gas pressure, and mining depth is established and simulated by using COMSOL Multiphysics software. Research results indicate that under the influence of factors such as high ground stress and gas pressure, the mutual coupling interaction between coal and gas is much more significant, which leads to the emergence of new characteristics of gas compound dynamic disasters. Reducing the ground stress concentration in front of the working face can not only minimize the possibility of rock burst accidents which are mainly caused by ground stress, but also weaken the role of ground stress as a barrier to gas, thereby decrease the number of outburst accidents whose dominant factor is gas; The results have a great theoretical and practical significance on the further optimization of accident prevention technique as well as safety protection of mines, disaster prevention system design, and accident emergency plans.
KEYWORDS : deep mining; high gassy coal seam; gas-solid coupling; dynamic disaster

1. INTRODUCTION

Most of the coal mines in China have reached deep mining, and the interaction among the constantly increasing coal seam ground stress, gas content, and gas pressure is blamed for the increase of gas compound dynamic catastrophes as well as some new emergent disaster characteristics.

On the basis of investigations concerning gas compound dynamic catastrophes in high gassy coal seams that have occurred in recent years, it has been discovered that there are obvious rock burst manifestations such as roof collapse, floor heave, and roadway deformation (often accompanied by high levels of gas gushing) at the scene of this new type of gas compound dynamic disaster. Moreover, there are some gas outburst holes at the scene and coal rock is thrown far away from these holes. Several distinctive features of gas outburst can be found in these accidents. All these illustrate that the coupling interaction between coal and gas in deep high gassy coal seams is more significant, which results in the emergence of new features of gas compound dynamic disasters.

Investigations aimed at coupling laws were made by domestic and foreign scholars. Litwiniszyn et al. studied the coupling interaction between coal and gas as well as gas migration law from different angles. Liu Jishan et al. built a mathematical model of gas-solid coupling which takes gas-coal's swelling deformation into account. Scholar Zhao Yangsheng took the lead in proposing a new mathematical model of the coupling reaction between coal rock and gas and further analyzed the numerical method. Zhao Guojing, Ding Jihui et al. came up with the instability theory of gas outburst and established a mathematical model based on the coupling relationship of a gas-solid two-phase medium. Liang Bing et al. set up a coal rock constitutive model which takes the gas interaction into account from the intrinsic time angle. Meanwhile, they proposed the destabilization theory of gas outburst/rock burst and established the mathematical model. Considering the fracture evolution process of coal, Yang Tianhong et al. developed a gas-solid coupling model of coal seam containing damage, and then simulated the gas drainage process in a deep coal seam. Tang Chunan, Xu Tao, Yang Tianhong et al. studied the numerical simulation of coal and gas outburst by using the relevant theory of fluid-solid coupling. S.Valliappan established a fluid-solid coupling model for the flow

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of coal-seam gas and compiled the corresponding finite element computer program to simulate the process of coal and gas outburst.

Mainly aimed at the characteristics of high gassy coal seams in deep mining, this paper simulated the laws of gas-solid coupling of coal-bed gas under the influence of gas pressure, mining depth, and other factors and then analyzed the influencing factors of gas compound dynamic disasters of coal rock in high gassy seams. The results have great theoretical and practical significance on the further optimization of accident prevention techniques as well as the safety protection of mines, disaster prevention system design, and accident emergency plans.

2. GAS-SOLID COUPLING THEORY OF COAL-BED THEORY

For ideal gas, the content of adsorbed gas satisfies the Langmuir equation and the gas seepage process conforms to Darcy's law, ignoring the effect of gravity and according to the law of conservation of mass at the same time, the following equations can been drawn.

1) The state equation of gas

The state equation of gas can be obtained based on the state equation of ideal gas.

$$\rho_g = \frac{M_g p}{RTZ} \quad (1)$$

With temperature being constant, then

$$\rho_g = \frac{\rho_n}{p_n} p \quad (2)$$

Where p is gas pressure, MPa ; ρ_g is gas density when the pressure equal to p, kg/m^3; M_g is molar volume of gas, mol/L; R is molar gas constant, kg/(m^3*MPa); Z is compressibility factor, the value is approximate to 1 when the temperature variation is not vast; T is absolute temperature, K; p_n is gas pressure in standard state, MPa; ρ_n is gas density in standard state, kg/m^3.

This can be simplified as:

$$\rho_g = \beta p \quad (3)$$

2) Gas content model

Gas in coal beds can be divided into two states; absorbed gas (Q_1), that is absorbed between micropore surface and coal particles, free gas (Q_2), which flows freely in pore fissure space.

When adsorbed gas content satisfies the Langmuir equation, then absorbed gas content formula of unit coal can be written as:

$$Q_1 = c\rho_c\rho_0 \frac{abp}{1+bp} \quad (4)$$

Where ρ_c is the density of coal, kg/m^3; ρ_0 is the density of gas under normal atmospheric pressure, kg/m^3; a and b are Langmuir adsorption coefficient, the dimension of a is $\mathrm{m^3/t}$, the value of a ranges from10 to 60, the dimension of b is $\mathrm{MPa^{-1}}$, the value of b ranges from 0.5 to 5; c is correction coefficient when consider factors such as coal moisture and ash temperature， the value of c ranges from 0 to 1.

Free gas content of unite coal can be expressed as:

$$Q_2 = \phi\rho_g \quad (5)$$

Where ϕ is coal porosity, dimensionless.

Above all, total gas content of unite coal is:

$$Q = Q_1 + Q_2 = c\rho_c\rho_0 \frac{abp}{1+bp} + \phi\rho_g \quad (6)$$

The operator form of which is shown as follows:

$$\frac{\partial Q}{\partial t} = -\nabla(\rho_g \boldsymbol{u}) + Q_m \quad (7)$$

Gas seepage process conforms to Darcy's law and ignores the effect of gravity, then:

$$\boldsymbol{u} = -\frac{k}{\mu}\nabla p \quad (8)$$

Where k is permeability of coal seam, m^2; μ is gas viscosity, Pa*s.

3) Porosity evolution model

Ignore the change of temperature and gas adsorption, evolution equation for coal porosity is:

$$\phi = 1 - \frac{1-\phi_0}{1+\varepsilon_v}(1 - K_Y\Delta p)$$

Where ϕ and ϕ_0 are coal porosity and original porosit, dimensionless; K_Y is coefficient of volume compressibility, dimensionless; Δp is pressure changes of gas, MPa; ε_v is volumetric strain of coal, dimensionless.

4) Permeability evolution model

Coal is a dual-porosity reservoir where gas is mostly stored in the coal matrix and Darcy fluid flow occurs in the natural fracture system. The flow capacity of fracture media depends almost entirely on the number and width of fractures and their continuity in the direction of flow. Permeability, a measure of the flow capacity, is directly related to a range of pore characteristics including pore size, continuity, and connectivity. It is generally believed that the change of coal permeability is decided by coal porosity. The Kozeny - Carman equation which is set up on the basis of the capillary model is most widely used. The permeability evolution model is:

$$k = \frac{k_0}{1+\varepsilon_v}\left[1 + \frac{\varepsilon_v}{\phi_0} + \frac{(1-\phi_0)K_Y\Delta p}{\phi_0}\right]^3 \quad (9)$$

3. NUMERICAL SIMULATION OF GAS-SOLID COUPLING IN DEEP HIGH GASSY COAL SEAMS

The general finite element analysis software COMSOL Multiphysic was adopted to make a calculation of the established gas-solid coupling model. The geometric model is 80 m long, 30 m high, the roof height of which is 15 m, floor height is 10 m, and coal seam height is 5 m. The excavation block whose length is 5 m is set at the far left of the coal seam.

3.1 Model parameter

According to the actual situation of high gassy mines in China and taking some relevant literatures as a reference, the model parameters are set up as shown as in Tables 1 and 2.

Table 1: Parametric values of coal and surrounding rock.

N	Value	Description
r1	1250[kg/m^3]	Coal density
E1	2713[MPa]	Coal elastic modulus
po1	0.339	Coal Poisson's ratio
co1	1.25[MPa]	Coal cohesiveness
theta1	37 π /180 [rad]	Coal inner friction angle
r2	2640 [kg/m^3]	Surrounding rock density
E2	33400[MPa]	Surrounding rock modulus
po2	0.235	Surrounding rock Poisson's ratio
co2	3.2[MPa]	Surrounding rock cohesiveness
theta2	π /6[rad]	Surrounding rock inner friction angle

Table 2: Parametric values of gas.

Name	Value	Description
rg	0.714[kg/m^3]	Gas density in standard state
e0	0.01	Initial porosity before excavation
k0	1.0×10^{-15}[m^2]	Initial permeability before excavation
mug	1.84×10^{-5}[Pa*s]	Gas viscosity
a	26[m^3/t]	Adsorption coefficient 1
b	0.714[MPa^{-1}]	Adsorption coefficient 2
c	0.9957	Adsorption coefficient 3
beta	7.14[kg/(m^3*MPa)]	Gas state coefficient
alpha	0.99	B-W coefficient

3.2 Simulation scheme and results

Mining depth is set at 800 m and initial gas pressure is 2 MPa. The gas-solid coupling laws of coal-bed gas are studied under the influence of great ground stress and gas pressure.

Firstly, the corresponding body load and edge load are exerted on the model, and the initial state before excavation is obtained. The distribution of vertical stress is shown in Figure 1.

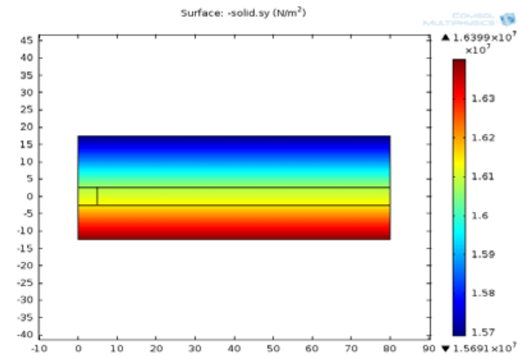
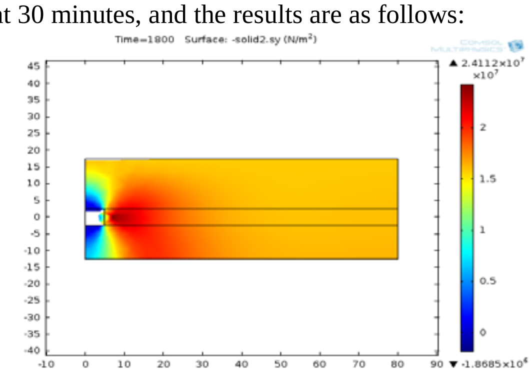
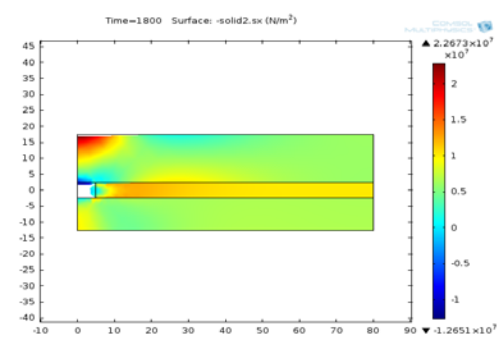


Figure 1: Distribution of vertical stress before excavation.

Excavate the preset block excavation. A transient solver is chosen to solve the gas-solid model of coal-bed gas. The duration is set at 0 to 60 minutes and the step size is 5 minutes. The parameters cloud maps are set at 30 minutes, and the results are as follows:



(a)



(b)

Figure 2: Distribution of vertical stress and horizontal stress after excavation.

From Figure 2, it can be seen that:

1) Obviously stress unloading area, stress concentration area, and initial stress area exist in the coal beds.

2) The maximum peak of stress lies in the stress

concentration area, close to the coal wall.

3) Obviously pressure-released region exists at upper and down floor of excavation roadway, the height of which is 10 m.

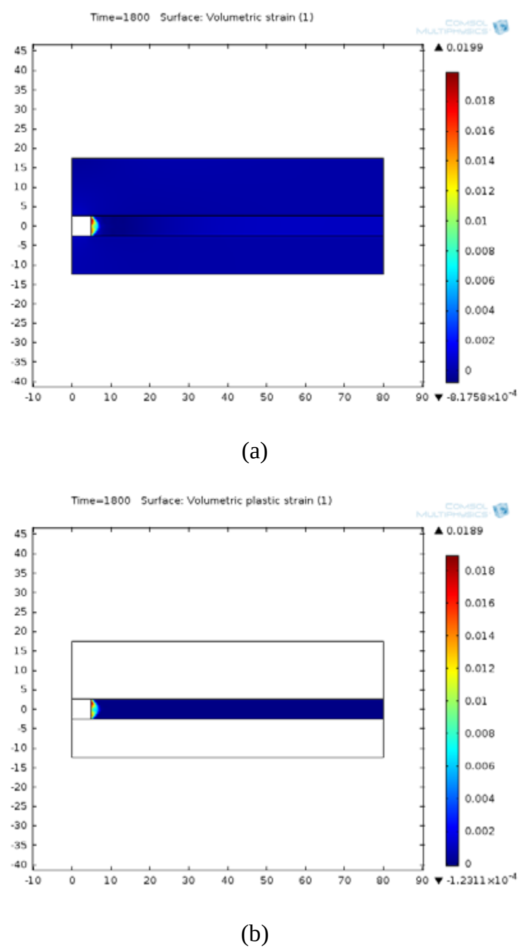


Figure 3: Distribution of volumetric strain and volumetric plastic strain after excavation.

From cloud maps of strain after excavation in Figure 3, we can see:

1) The stress of coal mass near the coal wall passes over the yield strength, plastic strain occurs, and the length of the plastic strain area is about 3 m.

2) Coal mass near the wall is forced and damaged, obvious dilatancy effect and volume expansion occur, then in the elastic region of stress concentration area coal mass is compacted and volumetric strain reaches the minimum.

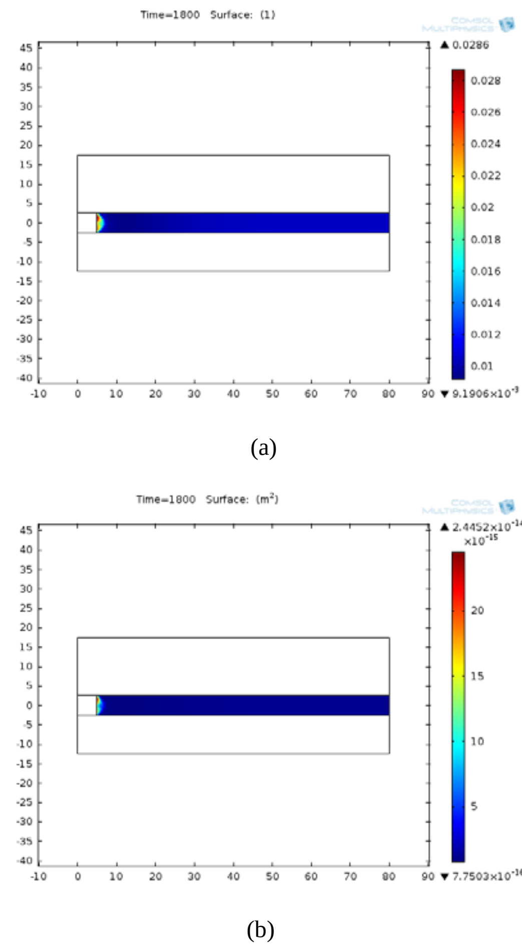
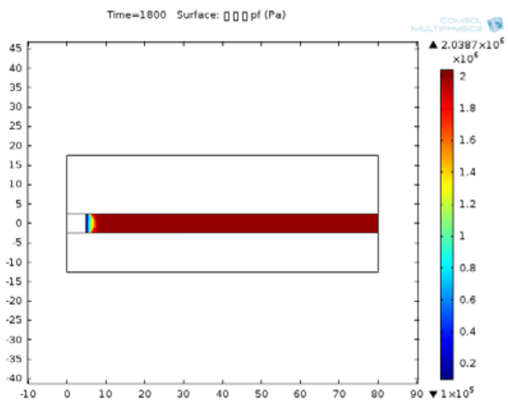


Figure 4: Distribution of porosity and permeability after excavation.

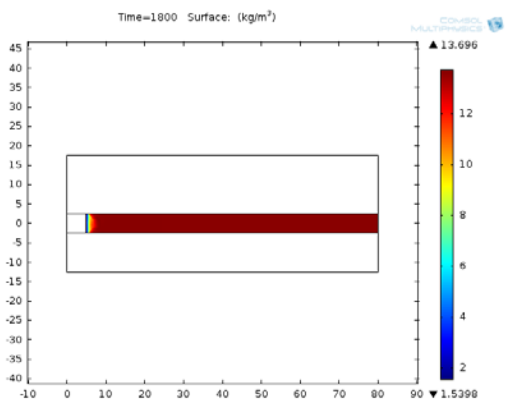
As cloud maps of porosity and permeability shown in Figure 4:

1) Porosity and permeability are all influenced by the strain of coal seams and the gas pressure, they have the same changing trend.

2) Because of the dilatancy effect, the porosity and permeability of coal mass near the coal wall are larger and reach the maximum at the coal wall, then gradually decrease along with the coal seam extends to right. Coal mass is forced and compacted in the elastic region of stress concentration. Porosity and permeability reach the minimum and then gradually recover to the original value.



(a)



(b)

Figure 5: Distribution of gas pressure and gas content after excavation.

What we can see from cloud maps of gas pressure and gas content are as follows:

1) Gas pressure and gas content share the same trend. They sharply reduce near the coal wall and reach the minimum there. They reach the maximum at areas where stress is concentrated, slightly greater than the initial values.

2) Due to the dilatancy damage of coal，gas is easy to outflow from coal seam in the pressure-released region. While at the stress concentration area, the compacted coal mass impedes the process of gas seepage and forms significant gradient differences of gas pressure and content.

4. GAS COMPOUND DYNAMIC CATASTROPHES OF DEEP GAS-FILLED COAL-ROCK

In order to analyze the effect of high ground stress and gas pressure on disasters, several gas compound dynamic catastrophes of deep gas-filled coal-rock are studied in this paper. The rock burst accident in Laohutai Fushun is taken as an example, and the results are shown in Table 3.

Table 3: Rock burst and gas emission situation in Laohutai Fushun Mines.

Ming depth /m	Total number of rock burst accident	Total number of gas concentration overrun	Percentage of gas concentration overrun /%
<580	165	1	0.61
630	224	13	5.80
680	269	34	12.64
730	135	10	7.41
780	337	83	24.63
830<	87	40	45.98
Sum up	1217	181	100

According to the analysis of the accident, it has been discovered that there are obvious rock burst manifestations such as roof collapse, floor heave, and roadway deformation (often accompanied by high levels of gas gushing) at the scene of gas compound dynamic disasters. Moreover, there are some gas outburst holes at the scene, and coal rock is thrown far away from these holes. Distinctive features of gas outburst can be found in these accidents. The gas gushing quantity per ton of coal is not very large, and the airflow reversal phenomenon is not significant.

Rock burst intensity is in direct proportion to concentration and duration of gas emission. Furthermore, in the coal seam that applied gas drainage measures, the frequency and strength of rock burst significantly increased. For the deep high gassy coal seams under the influence of high ground stress and gas pressure, the coupling interaction between coal and gas is more significant, which results in the emergence of new features of gas compound dynamic disasters.

5. CONCLUSIONS

1) A simulation of the laws concerning the gas-solid coupling of coal-bed gas was made by establishing a theoretical gas-solid coupling model under the influence of gas-pressure, mining depth, and using COMSOL Multiphysics software.

2) For deep high gassy coal seams under the influence of high ground stress and gas pressure, the coupling interaction between coal and gas is more significant, which results in the emergence of new features of gas compound dynamic disasters.

3) Reducing the ground stress concentration in front of the working face can not only work wonders for minimizing the likelihood of rock burst accidents which are mainly caused by ground stress, but also weaken the role of ground stress as a barrier to gas, thereby reducing the number of accidents whose dominant factor is gas. For deep high grassy coal seam, coal seam water infusion is the best method.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

Liang B, Zhang MT and Wang YJ (1995) The endochronic constitutional model of coal containing gas, Rock & Soil Mech., vol. 03, pp. 22-28.

Litwiniszyn J (1985) A model for the initiation of coal-gas outbursts. Int. J. Rock. Mech. & Min. Sci. & Geomech. Abstracts. , vol. 22(1), pp. 39-46.

Liu JS(2010) Linking gas-sorption induced changes in coal permeability to directional strains through a modulus reduction ratio. Int. J. Coal Geol., vol. 83(1), pp. 21-30.

Valliappan S and Wohua Z (1996) Numerical modeling of methane gas migration in dry coal seams. Int. J. Numer. Anal. Meth. Geomech., vol.20, pp. 571–593.

Xu T, Tang CA and Yang TH (2005) Numerical simulation of coupled gas flow in failure process of gassy coal-rock. Chin. J. Rock. Mech. & Eng., vol. 10, pp. 1667-1673.

Yang TH (2001) Study on infiltrate character and coupling analysis of seepage and stress in rock failure process, Shenyang, China: Northeastern University.

Zhao GJ and Ding JH (1998) Non-linear numerical simulation of coal and gas outburst as a coupling instability problem of solid-fluid biphase media. Journal of China University of Mining & Technology, vol. 02, pp.103-107.

Zhao YS (1994) Mathematical model of coal mass and gas coupling and its numerical method, Chin. J. Rock. Mech. & Eng., vol. 03, pp. 229-239.