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A Continuous Dynamic Prediction Model of Gas Pressure Based on Gas Emission at Excavation Face and its Engineering Application

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Abstract Gas pressure is one of the necessary conditions for the occurrence of coal and gas outburst. Realization of continuous and dynamic gas pressure forecasting is of significance for prevention and control of coal and gas outburst. In this work, we established a gas pressure prediction model based on the source of gas emission with considering fluid-solid coupling process. The verified results showed that the predicted gas pressure was roughly consistent with the actual situation, indicating that the prediction model is correct. And it could meet the need of engineering projects. Coal and gas outburst dynamic phenomenon is successfully predicted in engineering application with the model. Overall, prediction coal and gas outburst with the gas pressure model can achieve the continuous and dynamic effect. It can overcome both the static and sampling shortcomings of traditional methods, and solve the difficulty of coal and gas outburst prediction at the excavation face. With its broad applicability and potential prospect, we believe the model is of great importance for improving prevention and control of gas disasters.

Keywords: Gas emission; gas pressure; mining; coal and gas outburst

1 Introduction

Coal and gas outburst occurring in the coal mining process are dynamic phenomena accompanied by great hazards. This kind of disaster exists in almost all the main coal-producing countries in the world (Díaz Aguado and González Nicieza, 2007; Toraño et al., 2012). Among them, about one-third occurred in China. Thus, it is one of the major security issues in China coal mining (Guan et al., 2009; Skoczylas, 2012; Xu et al., 2006). With the mining depth and intensity continuously increasing and geological conditions gradually complicating, coal and gas outburst disasters will become more and more serious. Therefore, accurate prediction of coal and gas outburst becomes very important and urgent.

Conventional methods for prediction of coal and gas outburst are mainly drilling-based. These methods predict coal and gas outburst by measuring the initial velocity of gas emission from boreholes, the amount of drill cuttings weight, etc. Although their implementation has reduced the occurrence of coal and gas outburst effectively, outburst accidents frequently occur when the indexes are below the warning criteria or due to missed prediction. It's mainly because gas outburst is very complex. And miners experience is also a reason.

Therefore, some unconventional prediction methods, such as those based on changes in coal's mechanical property and coalbed thickness (Lat et al., 2007), as well as abnormal gas emission (Nie et al., 2014; Yang et al., 2010) and gas expansion energy (Jiang et al., 2015), etc., were proposed and applied in field trials, and obtained some results. In addition, geophysical methods such as electromagnetic radiation (He et al., 2012; Wang et al., 2011), microseismic (Lu et al., 2012) and acoustic emission (Lu et al., 2014) have also made great progress in coal and gas outburst prediction and been successfully applied in some coal mines.

Although there are a lot of prediction methods, gas outburst hasn't been completely eliminated. Gas pressure is one of the main factors inducing coal and gas outburst directly. And it's also one of the important indicators reflecting coal and gas outburst coalbed (Díaz Aguado and González Nicieza, 2007). Therefore, compared with the above methods, predicting coal and gas outbursts by gas pressure must have higher accuracy and universality. Since direct measurement of gas pressure in the excavation process has a great impact on coal production, prediction has drawn more and more attention by some researchers.

The initially gas expansion energy was used to determine critical gas pressure of gas outburst. And it was realized in the coal and gas outburst simulation experiments. The method has also been applied in some coal mines (Han and Jiang, 2005). Using gas desorption property, and residual gas content measured in the laboratory to fit and compute the coalbed gas pressure provides a new idea for gas pressure prediction (An et al., 2011; Wu et al., 2011). In addition, the safety line

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method for predicting gas pressure also met the needs in some coal and gas outburst mines (Wang et al., 2012). Moreover, the development of numerical simulation technology provides a new tool for predicting gas pressure. The finite difference method was applied to study the distribution of gas pressure and the characteristics of gas emission from areas around the excavation face and roadway (Gao and Hou, 2007). The distribution of gas pressure ahead of tunneling was analyzed when the gas content is assumed to be constant (Liang et al., 2011; Qi et al., 2007). Although these gas pressure prediction methods solved some field requirements to a certain extent, the dynamic behaviors of underground coalbed gas pressure are difficult to be truly reflected. It is very unfavorable for accurate prediction of coal and gas outburst.

In order to predict coal and gas outburst accurately, a continuous and dynamic predicting gas pressure is necessary and can be achieved by gas emission. On the one hand, gas emission during roadway excavation is the result of interactions between geological conditions and coalbed occurrence, and consistent with gas pressure impacting conditions. On the other hand, wide application of gas monitoring systems has inherent advantages in continuous and dynamic prediction of gas pressure using gas emission. No doubt, using such a method could solve the gas outburst prediction difficulty that has troubled coalmines for many years. Based on this, in this work, we established a continuous dynamic model to predict gas pressure at the excavation face based on gas emission. And verified and applied it into engineering by numerical simulation. We hope our research achieves continuous and dynamic pre-warning for coal and gas outburst.

2 Gas pressure prediction model

Gas emission is a fluid-solid coupling process and gas migration is driven by gas pressure gradient through coal seepage channels to excavation face. It involves desorption, adsorption, diffusion, etc. It is closely related to gas pressure. Thus, we can establish a gas pressure prediction model according to the sources of gas emission from the excavation face by considering fluid-solid coupling process.

2.1 Gas emission model

Because gas emission is originated from collapsed coal and coal wall, the intensity of gas emission on the excavation face can be described by

$$Q = Q_c + Q_w \tag{1}$$

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where Q_c and Q_w are the gas emission intensities from the collapsed coal and the coal walls, respectively, m^3/min.

Gas from coal wall is continuously supplied by coalbed, and affected by the fractures formed by underground pressure and coal damage, as well as mining procedures. Therefore, the intensity of gas emission in its attenuation process fluctuates greatly with changes in underground pressure and crack production. But in general, it obeys the law of exponential decay (Yu et al., 2000). By contrast, gas emission from collapsed coal is not affected by its supply source and underground pressure. Therefore, it does not fluctuate in its decay process.

2.1.1 Intensity of gas emission from collapsed coal

The intensity of gas emission from collapsed coal per ton and per minute is (Yu et al., 2000)

$$Q_1 = Q_0 e^{-\beta_1 t_1} \tag{2}$$

where Q_1 and Q_0 are the intensity of gas emission from collapsed coal at the time t_1 time and at the initial time, respectively, m^3/ (t.min); β_1 is the decay coefficient of collapsed coal gas, min^{-1}; t_1 is the time of the collapsed coal remains at the face, min.

The total intensity of gas emission from collapsed coal Q_c becomes:

$$Q_c = G_c Q_0 e^{-\beta_1 t_1} = X S_{cs} \gamma Q_0 e^{-\beta_1 t_1} \tag{3}$$

where G_c is the amount of collapsed coal by mining, t; X is the amount of footage at the face, m; S_{cs} is the cross section of roadway, m^2; γ is the bulk density of coal, t/m^3.

2.1.2 Intensity of gas emission from the coal wall

The intensity of gas emission from the coal wall is the intensity of gas emission from the excavation face wall plus the intensity of gas emission from roadway walls. Let the intensity of gas emission from a unit area of coal wall be q at the initial time, m^3/ (m^2.min), the intensity of gas emission from the face coal wall Q_f, [m^3/min] at time t_2, is (Yu et al., 2000)

$$Q_f = q S_{cs} e^{-\beta_2 t_2} \tag{4}$$

where β_2 is the decay coefficient of coal wall gas, min^{-1}; t_2 is the exposure time of coal wall, min.

Likewise, the intensity of gas emission from a unit area of roadway wall is

$$Q_3 = q e^{-\beta_2 t_2} \tag{5}$$

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where Q_3 is the amount of gas emission from a unit area of roadway wall at t_2 time, $m^3/(m^2.min)$.

Suppose that a small length segment along the roadway is *dl*, the rate of gas emission around the roadway wall along the *dl* obeys Eq.(5), the amount of gas emission from *dL at* t_2 is

$$dQ_3 = qe^{-\beta_2 t_2} Adl \tag{6}$$

where *A* is the perimeter of the coal wall, m.

After excavating *X* m, at the place *L* far away from the roadway head, the amount of gas emission from the roadway wall Q_r is the integral of Eq.(6) from the roadway head to the place *L*, that is,

$$Q_r = \int_0^{L+X} qe^{-\beta_2 t_2} Adl = qA(L+X)e^{-\beta_2 t_2} \tag{7}$$

According to Eqs.(4) and (7), the intensity of gas emission from the coal wall is

$$Q_w = q[S_{cs}e^{-\beta_2 t_2} + A(L+X)e^{-\beta_2 t_2}]. \tag{8}$$

From Eq.(8), it can be seen that gas emission from coal wall is closely related to the intensity of gas emission per unit area of the coal wall.

To obtain the intensity of gas emission per unit area of the coal wall, it is assumed that the process of coalbed gas migration is an isothermal process, free gas is an ideal gas complying with the ideal gas equation of state; coal is a continuous medium, plastic deformation of gas bearing coal is small, and the gas flow in coal wall is unidirectional and steady.

Gas adsorption obeys the Langmuir equation, the content of gas can be expressed as

$$X_m = \frac{abp}{1+bp} + Bnp \tag{9}$$

where X_m is the content of gas per unit coal mass, m^3/t; *a* is the limit adsorption amount of coal, m^3/t; *b* is the adsorption equilibrium constant, MPa^{-1}; *p* is the coalbed gas pressure, MPa; *n* is the porosity of coal; $B = T_0/(Tp_0\xi\rho)$, T_0 is the absolute temperature (under standard conditions, T_0=273 *K)*; *T* is the gas temperature, K; p_0 is the atmospheric pressure (under standard conditions, p_0 = 0.101325 MPa); ξ is the gas compression factor; *ρ* is the apparent density of coal, t/m^3.

Gas flow in the coal is in line with Darcy's law

$$u = -\frac{k}{\mu}\frac{\partial p}{\partial x} \tag{10}$$

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where u is the velocity of gas flow, m/s; k is the permeability of coalbed, m^2; μ is the coefficient of gas dynamic viscosity, MPa s; $\partial p/\partial x$ is the gradient of gas pressure, MPa/m. According to the ideal gas law, we converted the velocity of gas flow to volume flux. Hence, Eq.(10) can be written as

$$Q_v = -\lambda \frac{\partial p^2}{\partial x} \qquad (11)$$

where Q_v is the gas volume flux per day, m^3/ (m^2.d); λ is coal permeability ratio, $\lambda = Ck/2\mu p_0$, m^2/ (MPa^2.d), C is the unit conversion factor.

After introducing the volume flux per minute q, Q_v can be written as $Q_v = q/1440$.

So Eq.(11) can be written as

$$\frac{q}{1440} = -\frac{Ck}{2\mu p_0}\frac{\partial p^2}{\partial x} \qquad (12)$$

Therefore, putting Eqs.(12) into Eq.(8) one finds the intensity of gas emission from the coal wall to be

$$Q_w = [S_{cs} e^{-\beta_2 t_2} + A(L+X) e^{-\beta_2 t_2}](-\frac{720Ck}{\mu p_0}\frac{\partial p^2}{\partial x}). \qquad (13)$$

In addition, according to Eqs (9) and (12) as well as the law of conservation of mass, the relationship between gas pressure to the permeability becomes

$$\frac{\partial p}{\partial t_2} = \frac{pk}{\rho[\frac{ab}{(1+bp)^2} + Bn]\mu p_0}\frac{\partial^2 p^2}{\partial x^2} \qquad (14)$$

2.1.3 Model for continuous gas emission

Combining Eqs.(1), (3) and (13) one can obtain the model of continuous gas emission from the excavation face as follows:

$$Q = XS_{cs}\gamma Q_0 e^{-\beta_1 t_1} + [S_{cs} e^{-\beta_2 t_2} + A(L+X) e^{-\beta_2 t_2}](-\frac{720Ck}{\mu p_0}\frac{\partial p^2}{\partial x}) \qquad (15)$$

2.2 Model for gas pressure prediction

The fluid-solid coupling in the process of gas emission is very complex, thus it is necessary to introduce the dynamic evolution of the permeability of gas-bearing coal in the following (Perera et al., 2013; Wei et al., 2015):

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$$\frac{k}{k_0}=\left\{1-\frac{(p-p_1)(1\text{-}\varphi_0)}{(K-\Delta\sigma)\varphi_0}+\frac{4ac\rho RTK[\ln(1+bp)-\ln(1+bp_1)]}{9V_m K_j(K-p+p_1)\varphi_0}\right\}^3 \tag{16}$$

where k_0 is the coalbed initial permeability, m^2; p_l is the gas pressure of coalbed within the affecting extent of gas seepage, MPa; φ_0 is the coalbed initial porosity; K is the coal elastic modulus, MPa; $\Delta\sigma$ is the stress increment, MPa; c is the mass of combustible materials in a unit volume of coal, t/m^3; R is the universal gas constant, 8.3145 J/ (kg K); V_m is the molar volume of gas under standard conditions and equals to 22.4 L/mol; K_j is the elastic modulus of coal matrix, MPa.

Joining Eqs.(14), (15) and (16) one finds that the gas-emission-based gas pressure prediction model is as follows:

$$\begin{cases}\dfrac{\partial^2 p^2}{\partial x^2}=\dfrac{\rho[\dfrac{ab}{(1+bp)^2}+Bn]\mu p_0}{pk_0\left\{1-\dfrac{(p-p_1)(1\text{-}\varphi_0)}{(K-\Delta\sigma)\varphi_0}+\dfrac{4ac\rho RTK[\ln(1+bp)-\ln(1+bp_1)]}{9V_m K_j(K-p+p_1)\varphi_0}\right\}^3}\dfrac{\partial p}{\partial t_2}\\ \dfrac{\partial p^2}{\partial x}=\dfrac{-\mu p_0(Q-XS_{cs}\gamma Q_0 e^{-\beta_1 t_1})}{720Ck_0[S_{cs}e^{-\beta_2 t_2}+A(L+X)e^{-\beta_2 t_2}]\left\{1-\dfrac{(p-p_1)(1\text{-}\varphi_0)}{(K-\Delta\sigma)\varphi_0}+\dfrac{4ac\rho RTK[\ln(1+bp)-\ln(1+bp_1)]}{9V_m K_j(K-p+p_1)\varphi_0}\right\}^3}\end{cases}$$

(17)

with its initial and boundary conditions:

$$\begin{cases}p(x,t)\big|_{t_2=0}=p_1(0<x\le l)\\ p(x,t)\big|_{x=0}=p_0(t>0)\\ \left.\dfrac{\partial p}{\partial x}\right|_{x=l}=0(t>0)\end{cases} \tag{18}$$

where l is the affecting scope of gas seepage, m.

The model for predicting gas pressure is a set of complex nonlinear partial differential equations. Because it fully considers factors related to gas pressure including stress, as well as fluid-solid coupling process, we believe it should have a higher accuracy.

3 Numerical verification of gas pressure model

The gas pressure prediction model is a set of complex non-linear partial differential equations and that need to be solved through numerical simulation methods. Comsol Multiphysics can convert a multiple physics field coupling mathematical model into a unified system of partial differential equations. It can give the numerical solution closer to real physical process and avoid many errors caused by loosely coupled methods in resolving multi-field coupling problems. The software provides many solution modules with multiple commonly-used physical models and could customize PDE to numerically solve partial differential equation(s), achieving simulation of real physical phenomena.

3.1 Geological background

Liangbei Coal Mine is located at 37 km west of Xuchang City, Henan Province, China, as shown in Fig.1. It belongs to the Shenhuo Coal Industry Group. Its annual raw coal output is 900,000 tons. In its production process, the coal mine experienced many coal and gas outbursts, extrusion, rib spalling, floor heave, and serious deformation of roof and both sides of roadway.

Currently, the main coalbed of Liangbei Coal Mine is the No. 2_1 coalbed located at the bottom of the Permian Shanxi Formation. Fig. 2 shows comprehensive stratigraphic column of the Shanxi Formation of the No. 11131 excavating face at the scale of 1:200. The No. 2_1 coalbed has stable occurrence, relatively simple geological structure. Its average thickness is 4.53 m and average dip is 13° in the range of 8~15°. Its immediate roof is a 5.63 m thick dark gray sandy mudstone. The mudstone is a well-developed horizontal bedding, containing small visible muscovite flakes and rich plant fossils debris. Its main roof is a 3.33 m thick, gray, medium and grained sandstone. The sandstone is composed of dominantly quartz and minorly feldspar and black minerals. It contains a large amount of carbonaceous, muscovite chips and cemented siliceous mud. Its immediate floor is 8.64 m thick, dark gray, thin-layered, fine sandstone mixed with muddy strips with wavy bedding and contains a large number of plant fossils fragments; Its main floor is 0.3 m thick carbonaceous mudstone; Its original gas pressure is 0.6~3.65 MPa; Its gas content is about 5.73~13.97 m^3/t. The attenuation coefficient of gas flow from borehole per 100 m into the coalbed is 0.0313~0.2588 d^{-1} and coal permeability ratio is 0.0011~0.0454 m^2/MPa^2 d, so the coalbed is more difficult for gas drainage. The quality of coal is softer with its Protodyakonov coefficient being 0.15~0.25.

3.2 Model parameters

Our model is 100 m long and 100 m wide and uses the geological conditions of the No. 11131 excavating face of Liangbei Coal Mine as our prototype. Its roof, floor and coalbed thicknesses are fixed according to the actual situation, as shown in Fig. 3. The bottom of the model is subject to the fixed constraint, and all its boundaries are fixed. The excavation part is the dark blue bulk in Fig. 3 and the excavation distance is determined according to the driving footage.

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Gas flows only within the coalbed. Table 1 shows the model's initial physical parameters.

3.3 Numerical verification

Fig. 4 shows the intensity of gas emission from No. 11131 excavating face of Liangbei Coal Mine from May 6 to 30, 2015. From Fig. 4, it is clear that the minimal and maximal gas emission rates are 1.15 m^3/min and 1.24 m^3/min, respectively, with little change.

Fig. 5 shows changes in conventional indicators from May 6 to 30, 2015. From the graphs it is obvious that during this time, the minimal and maximal drill cuttings desorption indexes Δh_2 were 80 Pa and 100 Pa, respectively; the minimal and maximal drill cuttings weight S were 2.6 kg/m and 3kg/m, respectively; the minimal and maximal initial gas emission velocity ΔP were 5.2 and 6.1, respectively. Thus, all the conventional indicators were far below the warning criteria of risk and little change. It shows that there's not any coal and gas outburst risk and factors impacting gas emission including stress, gas pressure as well as coal physical and mechanical properties barely changed. And it is the main reason for relative stable gas emission during the period.

Measuring gas pressure takes several days or even months. So borehole gas content was measured on-site, and Eq.(9) was used to deduce the gas pressure by gas content. The simulated gas pressure based on the prediction model was verified from two respects, one is the coal seam gas pressure during May 6~30, 2015, and the other is the gas pressure distribution in the front of the face.

Fig. 6 shows the comparison between the simulated and deduced gas pressure during May 6~30, 2015. It can be seen from the figure that their deviation is 5.88~13.3%, indicating that the simulated results is roughly consistent with the deduced results.

Fig.7 shows that the comparison between the simulated and calculated distribution of gas pressure using that at 0:00 am of May 14 as an example. It can be seen from the figure that the relationships of both simulated and deduced gas pressure distribution to the drilling depth are roughly consistent with each other, with minimal and maximal deviation of 0.86% and 15.5%, respectively.

The above verification of the gas-emission-based gas pressure prediction model clear indicated that the model fully considers the factors related to gas pressure and has a higher accuracy. It is suitable for engineering needs.

4 Engineering application

Coal and gas outburst events have occurred in Liangbei Coal Mine for several times. For example, on June 29, 1999, coal and gas outburst occurred in the excavation process of main crosscut, discharging 180 tons of coal and 18,000 m^3 of gas; on July 8, 2009; coal and gas outburst happened during the opening of the No.2_1 coal seam at the return airway crosscut, ejecting 600 tons of coal and approximately 50,000 m^3 of gas. During the current production, coal and gas outburst phenomena, such as gas spurting from boreholes and drill-bit suction, happened many times. Gas is an important factor causing coal and gas outburst disaster. In China, gas pressure less than 0.74 MPa or gas content less than 8 m^3/t is regarded as no outburst risk. However, the No.2_1 coalbed of Liangbei Coal Mine has strong outburst risk, and low index coal and gas outbursts happened several times. And coal and gas outburst is very difficult to predict accurately. In Henan Province where Liangbei Coal Mine is located, more strict stipulation is made. Gas pressure less than 0.6 MPa or gas content less than 6 m^3/t is regarded as no out risk. Thus, application of our new gas pressure prediction method may help solve the coal and gas outburst prediction problem of Liangbei Coal Mine.

On August 16, 2015, workers at the 16:00 shift of Liangbei Coal Mine found that gas emission from the No.11131 excavation face rose slowly from 1.73~2.1 m^3/min from July 23 to August 16 and up to 2.18 m^3/min on August 16, as shown in Fig.8. The predicted gas pressure based on the new model reached 0.62 MPa. Thus, the excavation was stopped for drilling to test risk and relief stress and gas pressure. During the drilling process, a slight borehole-spurting phenomenon occurred. However, the impacts of geological structure and other related factors were not found.

The index of gas desorption from drill cuttings Δh_2 and the initial velocity of gas emission ΔP, but not the drill cuttings weight, were beyond their warning criteria. Fig.9 shows the measured conventional indicators on August 16, 2015. From Fig. 9, it is clear that before 16:00 on August 16, 2015, the index of gas desorption from drill cuttings Δh_2 was 100~140 Pa, the initial velocity of gas emission ΔP was 6~8, and the cuttings magnitude S was 2.2~3 kg/m, all of them were less than their critical values of outburst risks.

The above mentioned prediction verification proved that compared with the conventional indicators, the gas-pressure prediction model for coal and gas outburst can be used for continuous and dynamic prediction. And it overcomes the static and sampling shortcomings of traditional methods. The new method for coal and gas outburst prediction at the excavation face has advantages over the conventional method in the continuous and dynamic prediction.

5 Conclusions

We established a continuous dynamic prediction model of gas pressure in this paper. It's based on gas emission and considers fluid-solid coupling process. The simulated results according to the prediction model were roughly consistent with the actual situation. It's with errors in coalbed gas pressures in the range of 5.88~13.3% and in gas pressure distribution with the drilling depth increasing in the range of 0.86~15.5%. The gas pressure prediction model fully considers factors and has a higher accuracy. It can meet the needs of engineering.

The uses of gas pressure prediction model successfully predict the coal and gas outburst dynamic phenomenon occurring at the roadway excavation face of the Liangbei Coal Mine. Before its occurrence, all the conventional indicators of the face were below the critical values of outburst risks. This shows that the gas pressure prediction model, as a new method for coal and gas outburst prediction, realizes continuous and dynamic prediction for coal and gas outburst. And it overcomes the static and sampling shortcomings of the traditional prediction method. We believe it has broad applicability and great potential prospect.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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Figures legends

Fig.1 Geographical location of Liangbei Coal Mine.

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Figures

Fig. 1

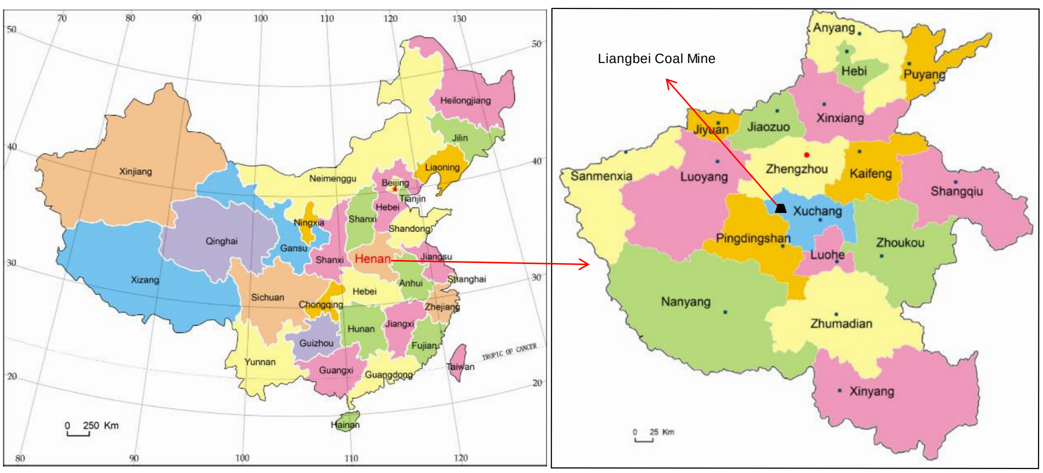

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Fig.2

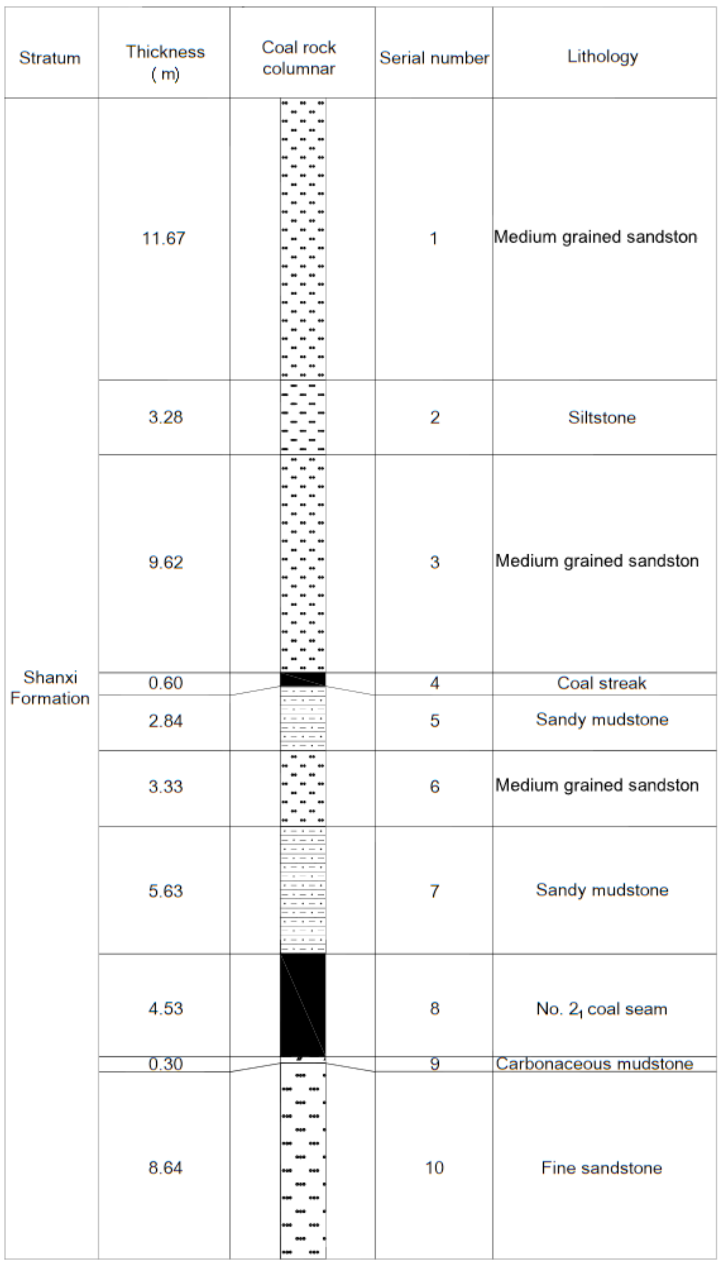

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Fig.3

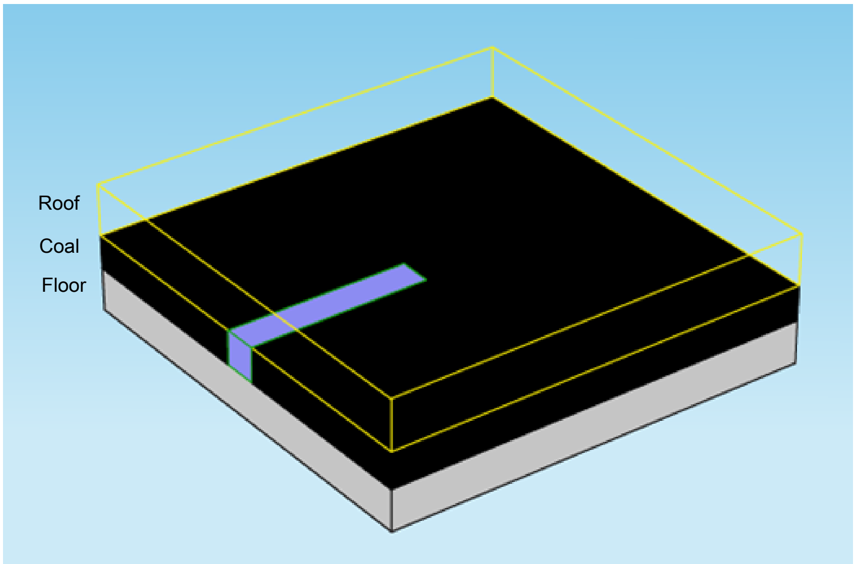

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Fig.4

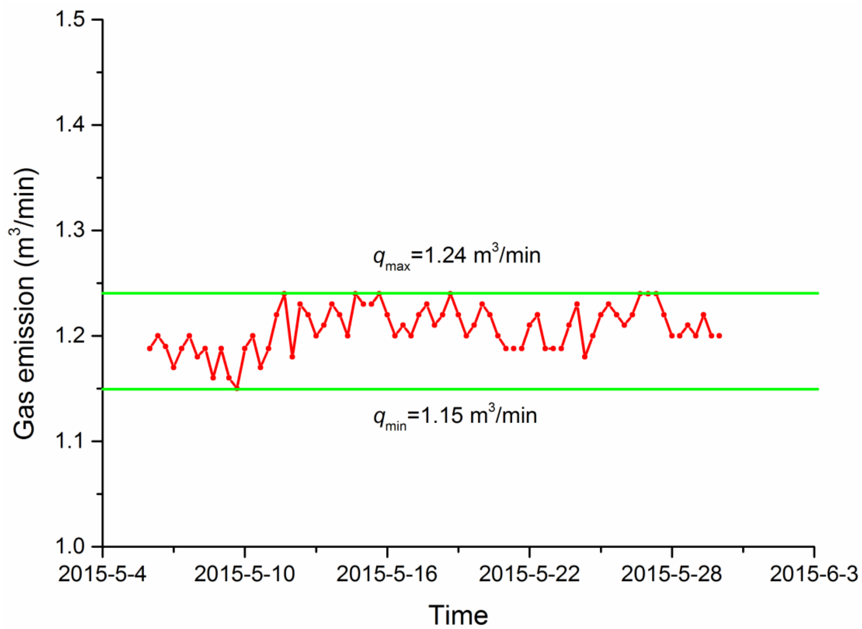

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Fig.5

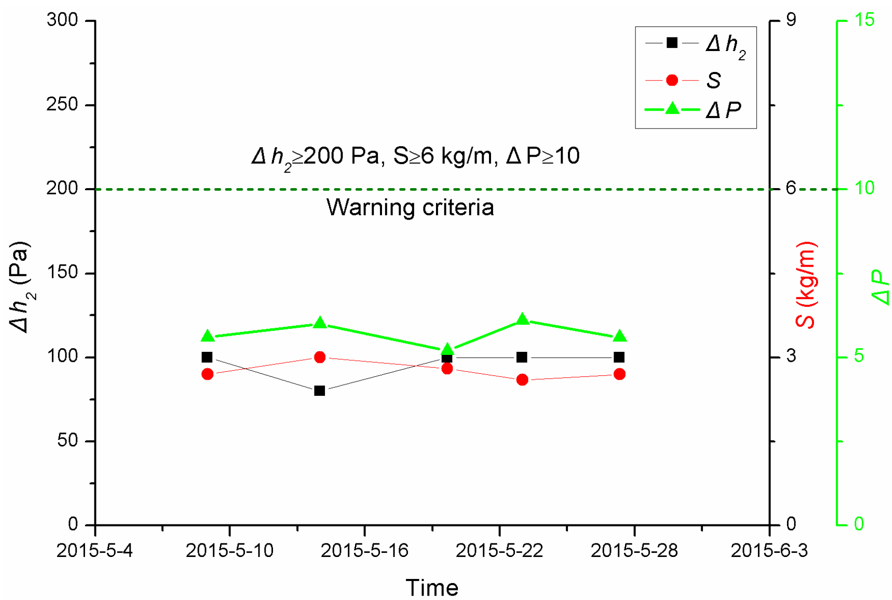

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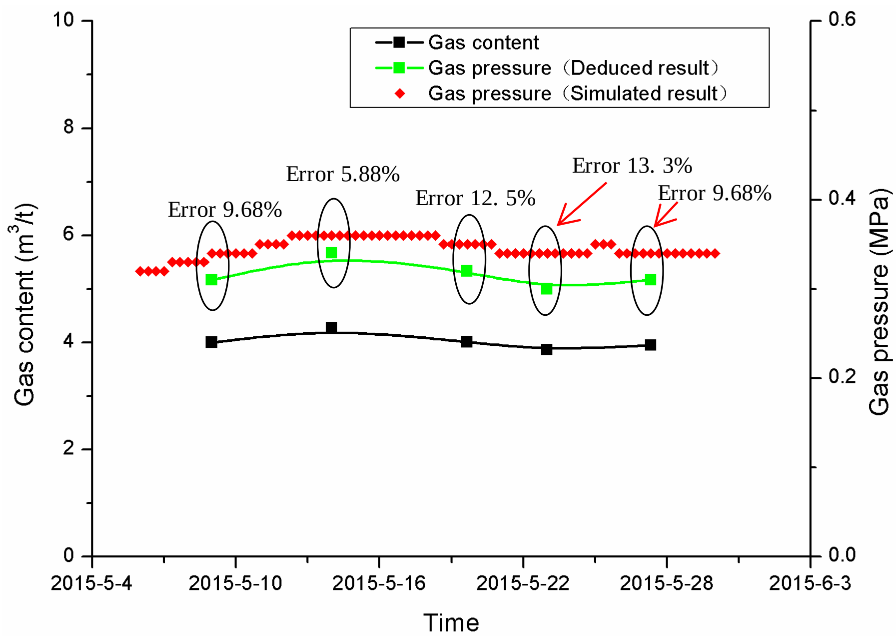
Fig.6



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425 Fig.7

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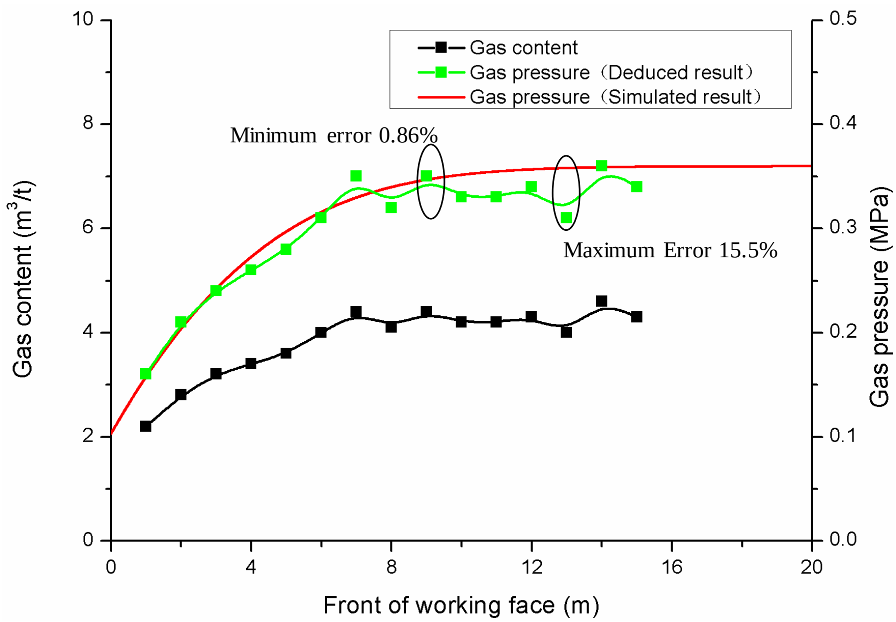

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Fig.8

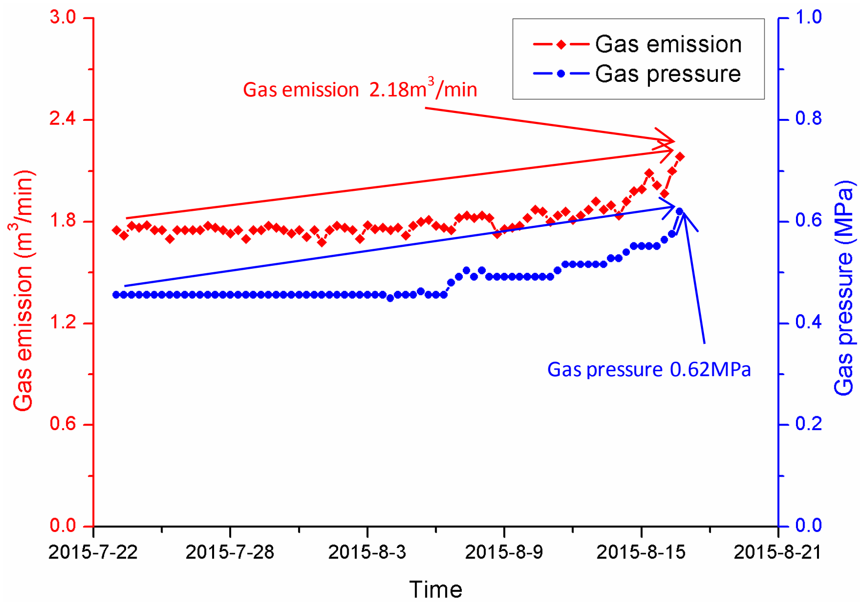

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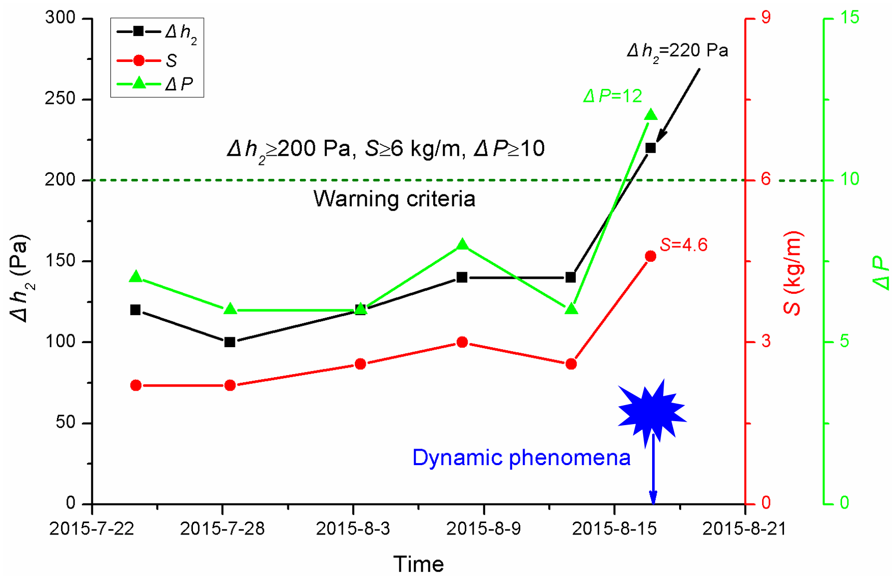
Fig.9



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Tables

Table 1 Basic parameters of the model

Parameter	Value
Elastic modulus of roof and floor rocks	30000 MPa
Poisson ratio of roof and floor rocks	0.22
Density of roof and floor rocks	2.5 t/m^3
Internal cohesive force of roof and floor rocks	40 MPa
Internal friction angle of roof and floor rocks	34 °
Elastic modulus of coal	3600 MPa
Poisson ration of coal	0.22
Internal cohesive force of coal	2.1 MPa
Internal friction angle of coal	30 °
Elastic modulus of coal matrix	6200 MPa
Limit adsorption amount of coal	30.7 m^3/t
Adsorption equilibrium constant	0.4 MPa^{-1}
Temperature	293 K
Mass of combustible materials in per volume coal	1.07 t/m^3
Initial porosity of coal	0.046
Initial permeability of coalbed	1.5×10^{-15} m^2
Kinetic viscosity coefficient of gas	1.84×10^{-5}Pa.s
Density of gas	0.717 kg/m^3
Atmospheric pressure at face	0.1 MPa
Area of roadway cross-section	12 m^2
Bulk density	1.4 t/m^3
Intensity of gas emission from initial collapsed coal	0.182 m^3/t.min
Decay coefficient of gas from collapsed coal	0.098 min^{-1}
Decay coefficient of gas from coal wall	0.0061 min^{-1}