First International Symposium on Mine Safety Science and Engineering

Research on the Coupling Effects Between Stereo Gas Extraction and Coal Spontaneous Combustion

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Abstract

In order to investigate the effects of the stereo gas extraction and overlying strata fracture development on the coal spontaneous combustion, through the research of air leakage channel and coal oxidative dynamic, we applied the U+H type fully machined workface of Shigang mine to study on the coupling between the stereo gas extraction and overlying strata fracture development, which caused air leakage and spontaneous combustion. The results show that the stereo gas extraction and overlying strata fracture development support air leakage passage and dynamic oxidation to coal spontaneous combustion in goaf and aggravated the process of coal spontaneous combustion. The study provides a new notion of controlling coal spontaneous combustion in the high gas and easily spontaneous combustion coal-seam of fully machined workface, which is of a certain theoretical and practical significance.

Keywords: Gas extraction; Fracture; Air leakage; Spontaneous combustion; Coupling

1. Introduction

Gas and coal spontaneous combustion are two of the main coal disasters, which seriously influence the production of coal mine. While gas disaster and spontaneous combustion are existing at the same time, the mine production and the personal safety would be doubly threatened. Especially in the high gas-containing and easily spontaneous combustion mines, use the gas extraction technology in the process of
mining, which caused air leakage intensified in goaf, which could cause spontaneous combustion due to the goaf broken residual coal. Find out the interactive effects between gas extraction and spontaneous combustion will be meaningful.

Li Zong-Xiang\textsuperscript{[1]} who used the air leakage percolation equation, the multi-component gas immiscible-diffusion equations and the integrated heat transfer equation, established the mathematical model of the coupling relationship of goaf spontaneous combustion and gas emission. Li Hua-Min\textsuperscript{[2]} had studied on the effects of rock activities on gas emission in work face, and analyzed the relationship between mining process and gas emission. Qu Qing-Dong and Xu Gia-Lin\textsuperscript{[3]} had researched on the effects of key strata activities on gas emission in adjacent layer, and proved that the impact of key strata movement on the control function of gas emission in adjacent layer. Cao Dai-Yong\textsuperscript{[4]} who chose geological factors as the breakthrough point, had studied systematically the important role that fissure system in coalfield namely formation of point, line, and the extended evolution dynamics. Zhao Cong\textsuperscript{[5]} had also analyzed goaf risked falling proportion of porous media of extreme irregularities and goaf air pressure and distribution by fuzzy seepage theory.

These researches show that the realization between the gas extraction and adjacent seams would be based on the fracture development of the overlying strata and pressure relief. But the fracture development of the goaf and the rock seams, and pressure relief, which could cause lots of coal-rock fracture, while plus suction pressure of the extraction system, could form both horizontal or vertical air-leaking passage and air leakage power. At the same time for easily spontaneous combustion seam, because of the caving affection and gas extraction, cause fracture development and air-leaking dynamic in the goaf and overlying strata, support oxidation power and aggravating the process of coal spontaneous combustion, which are harmful to the mine fire-prevention.

According to the actual situation of Shigang mine, where using stereo gas extraction in the U+II type workface, this paper mainly researches on the coupling relationship between the stereo gas extraction and coal-rock fracture, aims to analyze the effects of gas extraction and fractures evolution on spontaneous combustion.

U+II type workface ventilation and gas extraction technology\textsuperscript{[6]}, which is the most representative gas extraction technology of coal mine, provides an effective way of co-mining and gas. By the inner interlocked tail road and high extraction roadway, the gas extraction of the upper corner and overlying strata and pressure relief area of adjacent layer are realized. 15101 workface is one of four closed work- faces of YangQuan mines because the fire broke out, which affected the mine safety and the production progress, caused huge economic loss and social influence. Therefore, based on fire prevention, combining roadway arrangement and gas extraction system, we will research on the effects of the extraction system and the fracture development on the float coal spontaneous combustion, which are significant.

2. Seepage theory of float coal spontaneous combustion and dynamic oxidation

2.1. Porous medium Seepage theory

While the study of goaf seepage characteristics, coal-rock fragments body is usually regarded as porous medium. A porous medium or a porous material is a solid (often called frame or matrix) permeated by an interconnected network of pores (voids) filled with a fluid. Usually both the solid matrix and the pore network are assumed to be continuous, so as to form two interpenetrating continua such as in a sponge. Fluid flow in the porous medium is affected by the properties of fluid and porous medium. The main two parameters of porous medium are porosity $\varepsilon$ and permeability $k$.

The momentum conservation equation is expressed as:
\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = S_i \]  

(1)

Porous media are modeled by the addition of a momentum source term to Eq.(1). The source term is composed of two parts: a viscous loss term (Darcy, the first term on the right-hand side of Eq.(2)), and an inertial loss term (the second term on the right-hand side of Eq.(2))

\[ S_i = -\left(\sum_{j=1}^3 D_{ij} \mu v_j + \sum_{j=1}^3 C_{ij} \frac{1}{2} \rho |v| v_j \right) \]  

(2)

where \( S_i \) is the source term for Navier-Stokes equations, \( \mu \, (\text{kg/(m \cdot s)}) \) is kinetic viscosity of the gas, \( D \) and \( C \) are prescribed matrices. This momentum sink contributes to the pressure gradient in the porous media, creating a pressure drop that is proportional to the fluid velocity in the porous matrix. In laminar flows through porous media, the pressure drop is typically proportional to velocity. Ignoring convective acceleration and diffusion, the porous media model then reduces to Darcy's Law:

\[ \nabla p = -\frac{\mu}{k} v \]  

(3)

where \( k \) is the permeability, \( v \) is filtration velocity. The filtration velocity \( v \) (velocity averaged over the medium) is related to the intrinsic velocity \( V \) (velocity averaged over the pore space) by \( v = \varepsilon V \), where \( \varepsilon \) is the porosity. In order to tie in with Darcy’s results, the pressure here has to be an intrinsic quantity, i.e., the pressure is averaged only over the pore space.

The permeability \( k \) depends on the pore size (or particle diameter) \( D_p \), the porosity, and also on the detailed geometry. A useful estimate is given by the Carman-Kozeny relationship, derived for a packed bed of uniform spherical particles, namely

\[ k = \frac{D_p^2}{180 \left(1 - \varepsilon\right)^2} \]  

(4)

Darcy’s law means that the drag is linearly proportional to the velocity. This holds for small velocities (namely when the Reynolds number, based on the pore scale, is less than unity). However, this law breaks down for larger velocities. Dupuit and Forchheimer found empirically, for larger velocities, that the drag is a quadratic function of the velocity, and detailed historical account has been given by Lage (1998).

To recover the case of simple homogeneous porous media

\[ S_i = -\left(\frac{\mu}{k} \mathbf{v}_i + C_2 \rho |v| v_i \right) \]  

(5)

where \( C_2 \) is the inertial resistance factor, simply specify \( D \) and \( C \) as diagonal matrices with \( 1/k \) and \( C_2 \), respectively, on the diagonals (and zero for the other elements).

In flow through porous medium, the Reynolds number (Re), a dimensionless number expressing the ratio of inertial to viscous forces, is used as a criterion to distinguish between laminar flow occurring at low velocities and turbulent flow. A Reynolds number is defined for flow through porous media:

\[ \text{Re} = \frac{\rho v d}{\mu} \]  

(6)

where \( d \) is some length dimension of the porous matrix. Although, by analogy to the Reynolds number for pipes, \( d \) should be a length dimension representing the elementary channels of the porous medium, it is customary to employ some representative dimension of the grains for \( d \) (in an unconsolidated porous medium). Often the mean grain diameter is taken as the length dimension. Sometimes \( d_{10} \) is used, i.e., the grain size that exceeds the size (diameter) of 10% of the material by weight. The term \( d_{50} \) is also
mentioned in the literature as a representative grain diameter. Collin suggests \( d = (k/n)^{1/2} \), where \( k \) is permeability, and \( n \) is porosity, as the representative length dimension to be used in the Reynolds number. Ward uses \( k^{1/2} \) as the representative length \( d \). In practically all cases, Darcy’s law is valid as long as the Reynolds number based on average grain diameter does not exceed some value between 1 and 10. Some authors suggest Re 100 for the upper limit of the laminar flow regime, which is often referred to as the nonlinear laminar flow regime.

2.2. Sketch of face tunnel layout

The \( U^+ II \) type work-face with the inner interlocked tail road and high extraction roadway, the coal mine realizes gas extraction of the upper corner and overlying strata and pressure relief area of adjacent layer.

This paper takes 15101 workface of ShiGang mine (belongs to Yangquan mine area) as example, which represents the general situation of YangQuan mine area. 15101 workface, which is one of four fire work-faces, is pertinent and representative. The elevation of 15101 work-face is 952~997m, the elevation of ground surface is 1492~1375m, depth of burial is 423~517m. Strike length is 475m, inclined length is 152m, main coal seam thickness is 6.68~7.35m, average thickness is 7.02m, dip angle of the coal seam is 5°~14°.

Workface ventilation and gas control adopted inner interlocked tail road, widely used in recent years in the top coal caving faces. An “inner interlocked tail road” decorate where apart from the inner side of return airway 10 ~ 20m along the roof fracture zones basis on the traditional "U" type ventilation system, the high extraction roadway of 15101 fully mechanized caving face decorate along the 9# coal seam, apart from the 15#coal seam 53.9 m, the horizontal distance apart from return airway about 60m. Inner interlocked tail road is permanent in low pressure area, which makes it play a special role of discharging methane, reducing gas emission of upper corner, solves the problem of gas concentration exceeding limits in upper corner. At the beginning of mining, the function of high extraction roadway is not too large, but along with pushing forward of the working face, the first weighting of the old roof began appeared, the mining-induced fracture of overlying strata began gradually development, at this time back high extraction roadway and high extraction roadway would gradually perform function, the gas of adjacent layer gas will pour into high extraction roadway where gas concentration will increase, and the whole effect of extraction will get improvement greatly.

14# coal seam which is vertical 6 ~ 7 m above 15# coal seam and is not mined, but caving in the goaf along with the roof, makes the float coal thickness increased in goaf, the minimum thickness of the rock parting between 14# and 15# coal seam is 0.4m, which would make the two-layers float coal in some certain position overlap, cause the float coal thickness largent.

2.3. Effects of gas extraction and fracture development to spontaneous combustion

Based on the seepage theory of the mined-out area and coal-rock fracture and combined with the actual situation of gas extraction of 15101 workface, to find out the coupling crossing point of the gas extraction and coal-rock fracture development of float coal oxidation dynamic, is the starting point of the further research work. Through the analysis of the condition of float coal spontaneous combustion and actual working condition, having the conclusion that air-leakage passage and air-leakage power, and goaf air-leakage system are formed because of gas extraction and overlying strata fissure development, airflow under the action of the air-leakage power, diffused along goaf and overlying strata fracture, causing migration of stereo airflow, and the float coal in an effective oxygen supply environment, prompt the contact area and strength between float coal and oxygen increasing. Along with advance of workface and oxidation time increasing, coal float begin to oxidation and the temperature build-up, plus the temperature
difference on both ends of air leakage and fire pressure be formed by altitude difference, which aggravate air-leakage power and oxidation dynamic to float coal, and cause float coal oxidation aggregative, eventually cause spontaneous combustion occur.

3. Laws and features of fracture development of overlying strata

3.1. Fracture evolution of overlying strata

The overlying theory proposed by the research group headed by Qian Ming-gao academician\(^7\), provides theoretical basis for putting forward manifestations of scientific explanation for mine pressure of stope, prediction and control, forming the complete system of the mine pressure and control. Proposed “perpendicular three zones” on basis of the overall motion rule of the whole overlying strata and the surface rock stratum.

![Fig.1](image-url) the upper strata fracture development during different moving distance by UDEC

From Fig.1, we know that the height and the scope of the fracture development of overlying strata of the mining coal seam will gradually increase with moving distance of the workface, the investigating the situation of fracture development caused by the change of goaf overlying strata with workface mining, according with the condition of 15101 workface, use the UDEC4.0 and build the model of the workface, simulate the range and height of fracture development during different moving distance. With the
workface moving and the action of rock pressure, the pressure relief rock of the overlying strata fracture and sink, causing fracture more development.

3.2. Determining the fractures height in goaf

The basic roof of 15101 workface is made up of fine sandstone, immediate roof is siltstone and false leaf trace roof is mudstone, according to the hard rock stratum the fully-mechanized face fracture zones height of "building, water, railway and the setting of shaft and tunnel coal pillars and the pressured coal mining code", the empirical formula:

$$H = 100 \sum M / (1.2 \sum M + 2.0) + 8.9 \quad (7)$$

$$H = 30 \sqrt{\sum M + 10} \quad (8)$$

According to the condition of 15101 fully mechanized caving face, through the formula (7), get the calculation $H = 76.91$ m, through the formula (8), get the calculation $H = 91.61$ m. Consider the breakage degree of fully mechanized caving workface roof will far outstrips the mechanized coal face or slicing system workface, and because of the thick coal seam, the fracture zones height increases faster. The influence coefficient of fracture zones height in fully mechanized caving workface is 1.3, so the maximum fracture zones height of 15101 fully mechanized caving face is: $91.61 \times 1.3 = 119.09$ m.

Additionally, according to the roof lithology after exploiting of the workface, estimate the fracture zones height. As a general rule, maximum height of "water diversion, gas guiding " fissure formed is 9 ~ 12 times as high as mining height in soft rock, 12 ~18 times as high as mining height in medium harden rock layer, 18 ~ 28 times as high as mining height in harden rock layer. 15101 overlying strata of fully mechanized caving face belongs to medium harden rock layer, so the height of gas leading fracture zones in 15101 fully mechanized caving face is between 88.8 and 133.2 m.

Base on the theoretical analysis on the influence of the change of working face length on the height of gas leading fracture zones, the 15101 fully mechanized caving face length is 152m, calculate the theoretical height of gas leading fracture zones is 125.68 m, the results show that the general zones agree with empirical value 133.2 m. Therefore, under the geological condition of the face, when slanting length of fully mechanized caving face is 152m, the height of gas leading fracture zones is 125.68 ~ 133.2 m.

3.3. The distribution characteristics of coal-rock fracture

The fracture related to coal combustion what mentioned in this paper mainly refers to endogenous fissure, is the main channel of coal seam contact with air. Through the research on the caving of overlying strata of 15101 workface, distinguish the fundamental type of structural fissure, collapse fracture, pressure relief fracture. Face mining caused overburden failure and formed caving zone, fault zone and depressed zone, which caused the overlying strata fracture development and collapse. Coal seam dip angle of 15101 face is smaller, mining depth is more than 500 m, vertical fractures easily get to the inner interlocked tail road and high extraction roadway, communicated with residual coal in goaf and oxygen, created conditions for coal oxidation and autothermal. Overburden failure largely depends on strata structure, often develop along the structural fissure; on the other hand, collapse fracture is the product of coal seam mining which is restricted by mining engineering.

Through analysis of fracture development in the U+II type close distance coal seams, find that the meiobar from inner interlocked tail road and workface and return airway to goaf depth must exist to air leakage. At the same time through the calculation of goaf mining-induced fractures elliptic paraboloid zone height, vertical height of influence area is 125.68~133.2 m, because high extraction roadway of 15101 workface decorated along the 9# coal seam, apart from the 15# coal seam roof 53.9 m, so fissure
development can through the high extraction roadway, is favor for gas extraction, but the pressure difference between the high extraction roadway and work face, and thermal air pressure because of the temperature difference between the two ends, cause air flow surge up the high extraction roadway along the fracture, form another air leakage passage. Comprehensive consider the position of the inner interlocked tail road and high extraction roadway, formed grade separation leakage air sources in the U+II type closed coal mining-out area. Along with the mining of 15th coal seam, the roof collapse and appear breakage, form a mass of fractures. In the presence of air leakage dynamic, goaf constantly supplies fresh air flow to 14th and 15th coal, creating prerequisites for float coal oxiding. So coal-rock fracture development of U+II type workface is no advantage for fire, and easily causes float coal spontaneous combustion.

4. Influence of gas extraction to air leakage

The major difference between U+II type face and traditional U-shape working face is the roadway layout and the ventilation mode different. The core issues of the coupling of gas extraction and coal combustion is whether the stereo gas extraction technology can intensify air leakage, so it is necessary to unfold the work.

4.1. Measurement analysis the air leakage during first weighting and periodic weighting

At the beginning of mining, before the main roof first weighting, measured the ventilation parameters when the high extraction roadway still didn't play a role in extraction. after working face advanced certain distance, and periodic weighting appeared, and the high extraction roadway react, measured the ventilation parameters again, and compared the air-leakage state under the same air supply condition. The measured data showed in Table 1.

| Measured stage       | Promote distance/m | Intake airway | Return airway | Inner interlocked | High extraction | Air leakage |
|----------------------|--------------------|---------------|---------------|-------------------|-----------------|------------|
| Before first weighting| 12.0               | 2800          | 1103          | 1613              | 0               | 84         |
| Periodic weighting   | 49.2               | 1750          | 1042          | 453               | 126             | 149        |

During the normal mining after periodic weighting, the high extraction roadway extracted the gas of adjacent layer area, through analyzing the gas composition in the high extraction roadway, the gas average concentration is 40%, the quantity of extraction of high extraction roadway is 126m³/min, the air occupancy was 75.6 m³/min, therefore, under the action of the inner interlocked tail road and high extraction roadway, the goaf air leakage actually existed.

4.2. Air leakage numerical simulation analysis

The flow field distribution of air-leakage in goaf largely impact on coal spontaneous combustion, suitable oxygen concentration is favorable to coal spontaneous combustion. Research on the response to the flow field distribution under the condition of stereo gas extraction, which is great significance to the prevention of coal combustion. According to mining condition of 15101 work face and fissure development characteristics of overlying strata, through the simulation [8-12] by FLUENT on the leakage flow field in the goaf and the overlying strata pressure relief regional zone, find the goaf flow field presents three-dimensional changes, which largely influenced by the high drainage extraction and inner interlocked, as shown in Fig.2, Fig.3 and Fig.4.
Fig.2 Model for Numerical Analysis with the Ventilation of 15101 workface

(a) above 1.5m coal floor  (b) above 7.0m coal floor and the location of inner interlocked tail road

Fig.3 The air flow lines within the caved zone in horizontal plane in 15101 goaf (m/s)

Fig.4 The air leakage speed in 15101 goaf

Through the numerical simulation, found the air leakage presented one source and three confluences by the role of inner interlocked tail road and high extraction roadway in goaf, cased the air leakage stereo changes in dip and strike during the mining. The fracture development and the overlying strata pressure relief provided the air leakage passage, which cased the air flow in the goaf.

5. Stereo gas extraction & overlying strata fracture development induce spontaneous combustion

Through the research of air leakage and the analysis of fissure evolution in 15101 face, found that stereo gas extraction is easy to cause air leakage, to the easily spontaneous combustion coal seam speaking, gas extraction increased the risk of coal spontaneous in certain degree, forming the foundation of coal oxygen compound dynamic. The coupling relationship is that gas extraction and the fracture development of overlying strata form air leakage passage and dynamic, meanwhile because of the tendency of easily spontaneous combustion, prompt coal combustion happened[13]. The model relationship is shown in Fig.5.
6. Summary and Conclusion

1) Analyses the interaction between the stereo gas extraction and fracture development of overlying strata, and the oxidation dynamic of float coal in goaf, which provides air-leakage passage and oxidation dynamics of coal spontaneous combustion, and threat to the float coal spontaneous combustion preventing and controlling.

2) With the empirical formula, research the situation of the overlying strata and the distance change of workface advances, calculate the height of 1510 work-face fracture zones evolution, and obtain the position of high extraction roadway that is in fissuration and development area, which formed the vertical air-leakage passages between rock fracture and the high extraction roadway.

3) Through the actual air leakage measurement and numerical simulation, find the air leakage was increased in goaf and the air flow migrated the risk of float coal combustion stereo gas extraction.

4) Under the situation of the process of gas extraction and adjacent layer fracture development, establish the model of between stereo gas extraction and coal rock fracture development induce coal combustion.

Acknowledgements

The financial support by the Research Fund of the State Key Laboratory of Coal Resources and Mine Safety, CUMT (10KF01), and National Natural Sciences Foundation of China (Grant No. 50974055) is deeply appreciated.
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