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Review

Control of coal and gas outbursts in Huainan mines in China: A review

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ABSTRACT

Coal extraction in Huainan area is basically characterized by one of typical multi-seam mining conditions observed in China, where coal is mined in soft seams characterized by high gas content, high stress, low permeability and difficult geological conditions. The average mining depth in Huainan area is 875 m and continues to increase by 15–25 m annually. The rise in mining depth increases the risk of coal and gas outbursts and makes it more difficult to control outburst risk in Huainan coalmines. This paper reviews the main achievements (e.g. theories, technologies and equipment) in outburst control in Huainan, and tries to analyze some key challenging issues, and to present associated strategies to address these issues. It suggests that the outburst control in Huainan must take a combination approach of both regional and localized control in which the former plays a dominant role. Other outburst prevention principles include (1) non-outburst seams protecting outburst seams, (2) less outburst-prone seams protecting strong outburst-prone seams, (3) stress-releasing mining, and (4) the combination of ground and underground gas drainage (the model is dubbed as "walking on two legs"). The paper concludes that we should conduct fundamental researches on outburst mechanism, and develop outburst control technologies and equipment to ensure safe and efficient coal mining of deep coal resources in Huainan area.

1. Introduction

Coal in Huainan area is basically mined in highly gassy and geologically complex conditions. Huainan used to be one of mining districts characterized by various coalmine gas disasters. A total of 145 outbursts have been recorded in Huainan from 1897 to date. Between 1980 and 1997, a total of 17 coalmine gas accidents were reported with 392 lives lost, and the fatality rate per one million tons of coal production was as high as 4.01. As mining intensity increases, shallow coal resources in Huainan start to deplete, and the average mining depth reaches 875 m and continues to increase by 15–25 m annually in association with high risk of outbursts of coal and gas. It is therefore imperative to minimize or mitigate the outburst risks and ensure safe and productive mining of deep coal resources in Huainan and other mines with similar geological conditions in China.

The coalfield in Huainan is located in the eastern region of China, the southern part of the Huaibei Plain in Anhui Province, a boundary area between the Huaibei Plate and the Yangzi Plate, and adjacent to the Qinling-Dabieshan tectonic zone. The coalfield covers an area of 3000 km^2. The coalfield has 50 $\times$ 10^9 t of coal resources and 592.8 $\times$ 10^9 m^3 of coal seam gas reserve. Within a depth 1000 m below the ground surface, the geological coal reserve is 17.5 $\times$ 10^9 t and the coal seam gas reserve is 300 $\times$ 10^9 m^3 approximately (Shang et al., 2001; Yuan, 2006; Zhao and Liao, 2007). The geological structure of the coalfield is a synclinorium oriented in NWW-EW direction. The coalfields are formed in the Carboniferous and Permian periods, and the main coal-bearing sections are located in the Shanxi, Xiashihezi and Shangshihezi groups. The coal measures are 750 m thick, and contain 26 coal seams located at the depths from 300 m to 1500 m below the ground surface. Fifteen of the seams are mineable, with a maximum thickness of 34 m.

The coal seams in Huainan are characterized by high gas content (12–36 m^3/t), high gas pressure (up to 6.4 MPa), great depth (300–1500 m below the ground surface), thick overburden (200–600 m), and high stress (the maximum principal stress of 26.8 MPa at the depth of 1000 m). They also have the characters of low strength (hardness coefficient f = 0.2–0.8), low permeability (0.0011 m^2/(MPa^2 d)), high geothermal feature (the maximum field temperature of 45 °C), multi-seam mining conditions (8–15 seams), high outburst risks (all of the 12 mines in operation are outburst-prone

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mines), and extremely complicated geological structures (about 6000 faults have been observed) (Yuan, 2007).

2. Main achievements in outburst control in Huainan

2.1. Fundamental theories

2.1.1. Theory of integrated coal mining and gas drainage

Extensive engineering practices in Huainan coalmines show that the traditional theory of “gas control in its isolation” and the direct application of advanced technologies from USA, Germany, and other regions in China could not properly prevent the occurrence of gas outburst in Huainan area. Considerations should be given to both coal mining and gas control, and coal seam gas has to be effectively drained prior to mining instead of merely relying on mine ventilation to dilute and vent gas out. Effective methods must be developed to de-stress coal prior to mining and enhance its permeability to achieve integrated coal mining plus gas drainage. The specific theoretical achievements in integrated coal mining and gas drainage are described as follows.

(1) The relation among stress, gas pressure, seam permeability, and strata movement in highly gassy coalmines has confirmed that de-stressing can significantly increase seam permeability, with which crustal stress and permeability are strongly correlated. With stress reduction, seam gas pressure can drop from 5 MPa to 0.74 MPa, allowing 90% of adsorbed seam gas to be desorbed into free gas, which significantly enhances seam permeability. Mining of a risk-free seam can result in deformation, stress reduction and permeability enhancement of its overlying and underlying strata. A good understanding of the mining-induced stress field, fracture field, de-stressed zones, and intensively fractured zones with respect to mining sequence, gas flow channels and the formation of gas-rich zones is critically important (Fig. 1).

(2) A recent coalmine case in Huainan was used to conduct field monitoring and testing as well as fundamental studies on stress, fracture and gas fields when its first seam was mined. The studies can facilitate the development of the theory of integrated pillarless coal mining and gas drainage with Y-type ventilation, as shown in Fig. 2 (Yuan, 2008a, 2008b; Yuan et al., 2013).

(3) A concept of the ratio of vertical stress reduction ($r = 1 - \sigma_z/\sigma_{z0}$, σ_z is the vertical pressure after mining, σ_{z0} is the original pressure) in the roof above a goaf has been proposed. The larger the value of r, the higher the degree of stress reduction resulting from mining (Fig. 3). Studies have also revealed the existence of an annular-shaped overlying gas-rich zone in

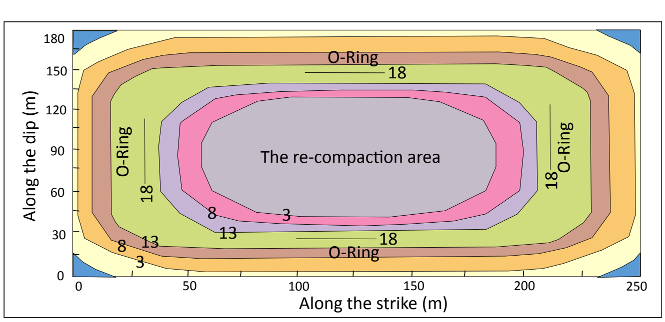


Fig. 1. O-ring fracture distribution and gas flow channels. The stress of mined-out area is given in the form of contour lines (unit: MPa).

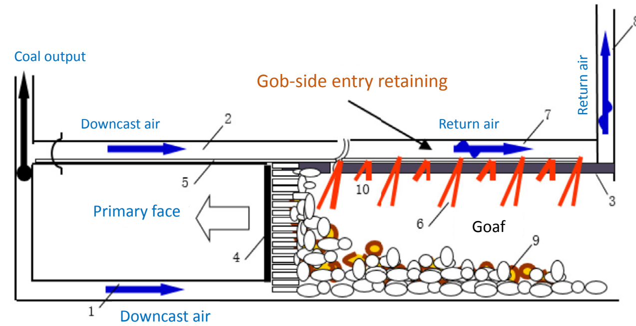


Fig. 2. Integrated pillarless coal mining and gas drainage with Y-type ventilation. Number 1 is panel air intake, 2 is secondary air intake, 3 is filled sidewall, 4 is longwall face, 5 is gas drainage pipelines, 6 is roof gas drainage boreholes along the face, 7 is panel air return, 8 is main air return, 9 is goaf, and 10 is floor gas drainage boreholes along the face.

multi-seam mining, and the basic geometric features of high efficient gas drainage range have also been understood (Yuan et al., 2011a, 2011b). The zone is located at a certain height above goaf with a certain width, and extends along vertical direction with a certain angle, as shown in Fig. 4.

(4) An “arch in arch” theory has been proposed for the roof strata structure above a retained goaf-edge gateroad. Studies have shown spatio-temporal evolution of the “arch in arch” structure, characteristics of staged fracturing in goaf, formation of stable fracture development zones near the roof wedge, outline of roof compaction area, and lower boundary of gas buoyancy. The interconnection of stable fracture zones around goaf results in formation of a fan-shaped gas-rich zone (Fig. 5).

2.1.2. Theory of gas content based outburst prediction methods

An outburst of coal and gas can be considered to be a process of energy transfer. Energy for outburst initiation is accumulated from the potential elastic energy of coal, its roof and floor strata, and the internal energy of gas in coal and strata. The latter is believed to be dominant. During gas outburst, the accumulated energy is transferred to the works in the forms of coal fragmentation and movement, frictional heat, vibration, and sound, etc. Of the potential energy, the internal energy of gas in coal is a dominant energy source. A quantitative relationship has been established between

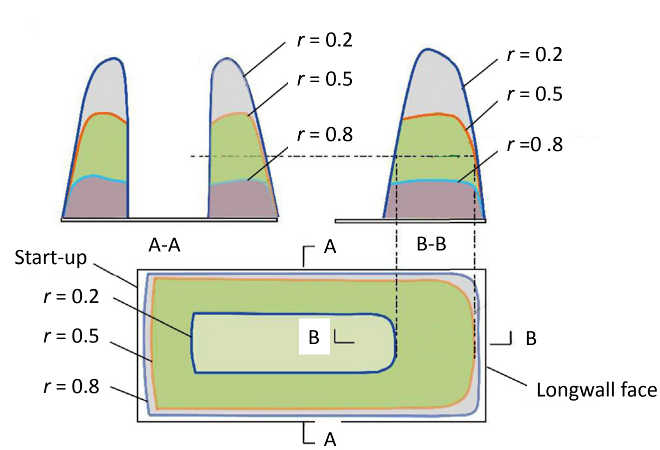


Fig. 3. A conceptual model of the stress reduction ratio.

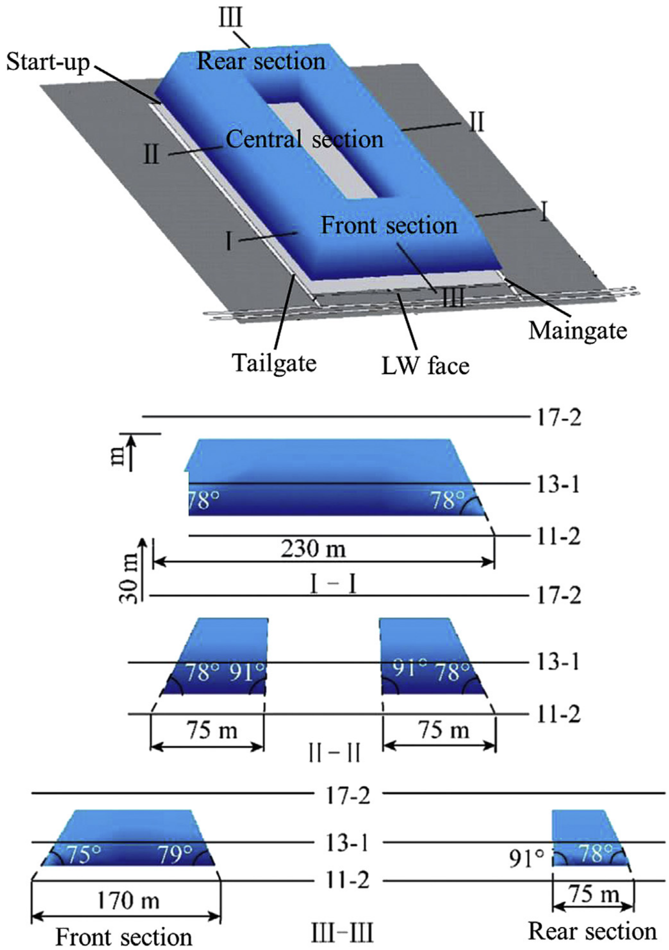


Fig. 4. An annular-shaped overlying zone. "LW face" means longwall face.

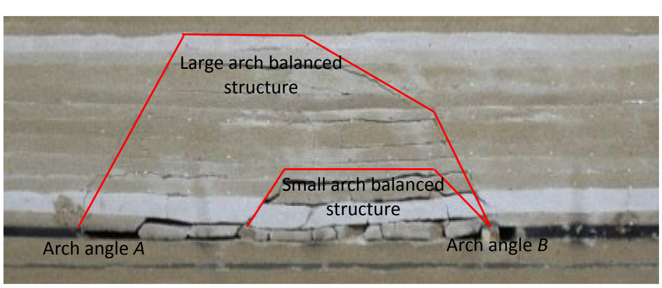


Fig. 5. The "arch in arch" structure and fan-shaped gas-rich zone.

gas content in coal and outburst potential (Valliappan and Zhang, 1999). Gas content in coal is directly associated with the internal energy of gas in coal (both free gas and adsorbed gas), and the value of gas content dictates the potential energy available for outburst initiation, which is written as

$$\zeta = \frac{3\Phi E\left[p - \left(\frac{p}{p_0}\right)^{1/n} p_0\right]}{8(\eta - 1)(1 + \nu)(\sigma + p)^2} + \frac{9\lambda BE}{4\sqrt{\pi}(1 + \nu)(\eta + 1)}\left(\frac{4DT}{d^2}\right)^n \frac{\left(\frac{p_0}{p}\right)^{1/n}}{(\sigma + p)^2} \quad (1)$$

where ζ is the ratio of internal gas energy to the necessary work to be conducted for prevention of outburst occurrence, Φ is the coal porosity, E is the elastic modulus of coal, p is the gas pressure, p_0 is the atmospheric pressure, η is the gas adiabatic parameter, ν is the Poisson's ratio, σ is the mean hydrostatic stress in rock, λ is the gas energy released due to desorption of a unit volume of gas, B is the initial gas content in coal, n is the Airey's constant, D is the diffusion coefficient for gas, and T is the period of gas outburst.

2.1.3. Experimental study of outbursts

(1) The composition and ratio of a similarity material for gas-bearing coal and its preparation process have been developed. The material consists of coal particles, sodium humate and hydrosolvent. Physico-mechanical characteristics of outburst coal have been analyzed and the similarity criteria have been developed. Test specimen can model coal with uniaxial compression stress of 0.5–3 MPa, while maintaining similarity of the physico-mechanical and adsorption/desorption characteristics as those of coal.
(2) A medium-scale system for physical outburst modeling has been constructed (Fig. 6a). A total of 22 outburst tests of orthogonal design have been conducted with three variables (stress, coal strength and gas pressure). The tests have improved our understanding of the mechanism of outburst occurrence under various combinations of stresses, coal strengths and gas pressures.
(3) A large-scale system for physical outburst modeling has been built (Fig. 6b). The system is the largest to date (3300 mm long, 3250 mm wide, and 4100 mm high), which is a truly triaxial testing system. The system mass is 150 t and the maximum loading at the boundary of the model is 5 MPa. A series of fundamental outburst studies is undertaken with the system.
(4) A large-scale system for physical modeling of integrated coal mining and gas drainage has also been developed (Fig. 6c). The dimension of the system is 5264 mm long, 4880 mm wide and 4100 mm high, and its mass is 170 t. The maximum loading at the boundary of the model is 5 MPa and the system can model a mining depth of 1500 m. A series of fundamental studies on integrated coal mining and gas drainage is also conducted with the system.

2.2. Key technologies and innovative equipment

Achievements in key technologies and innovative equipment are classified in terms of their applications related to outburst control. These applications include mine geology, outburst risk mitigation through regional and localized stress reduction in multi-seam mining of low permeability, outburst risk mitigation through an integrated approach of both surface and underground gas drainages, integrated pillarless coal mining and gas drainage with retained goaf-edge gateroads and Y-type ventilation, coal sampling in soft seams, quick and accurate measurements of seam gas content, and rapid coal uncovering in rock crosscut development.

2.2.1. Mine geology

Mine gas control will be very difficult without sufficient understanding of mine geology. In Huainan, we have undertaken extensive studies on exploration drilling, geophysical and geochemical methods, and developed key technologies for more accurate interpretation of surface-based 3D seismic data (computed tomography (CT) technology for surface geology), underground geophysical exploration (CT technology for underground geology), geological survey, informatization of mine water

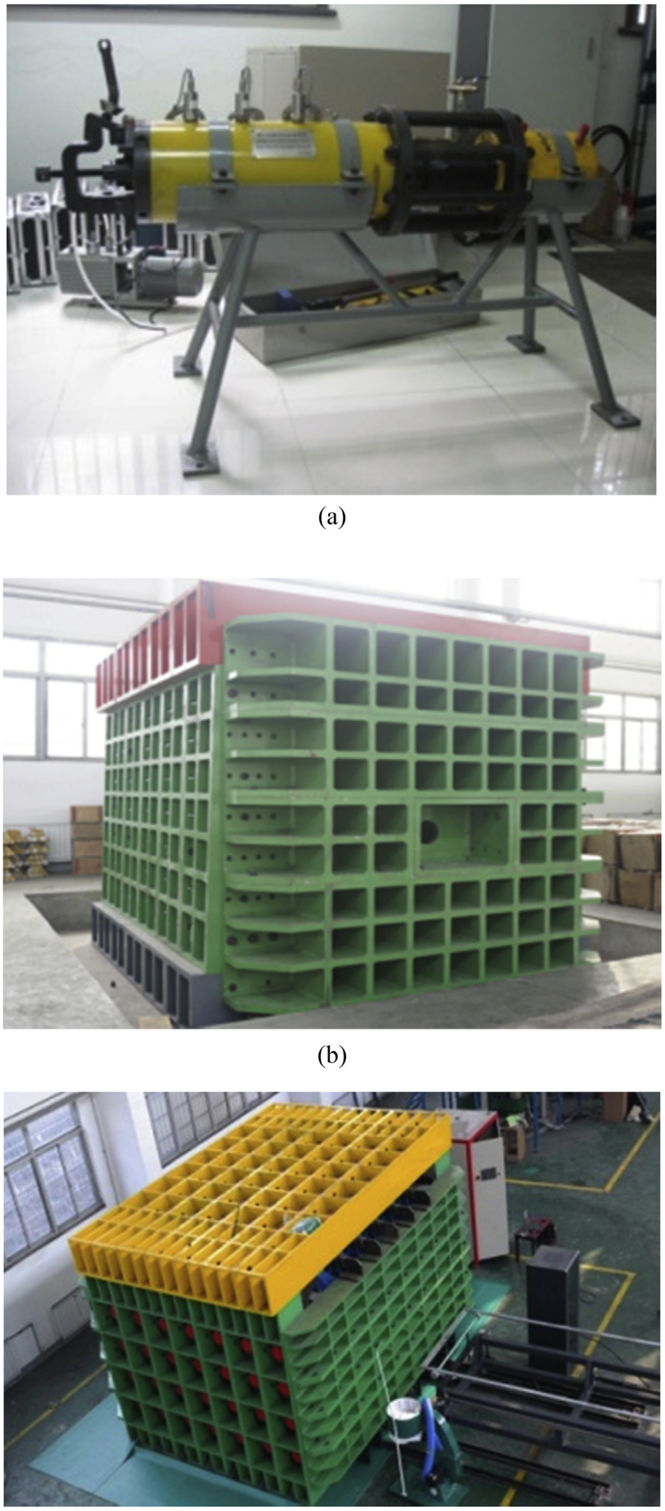


Fig. 6. Test systems for outburst-related study. (a) A medium-scale system for outburst modeling, (b) A large-scale system for outburst modeling, and (c) A large-scale system for integrated coal mining and gas drainage modeling.

management, identification with geochemical methods ("DNA" of geology), and coal seam gas geology. With these technologies, we are able to detect any faults of more than 3 m in length, dykes, cavities, and intrusions of igneous rocks which may have significant impacts on gas in coal.

2.2.2. Outburst risk mitigation through gas drainage from de-stressed seams in multi-seam mining of low permeability

Gas drainage targets the gas in the de-stressed and fractured zones in protective mining (Fig. 7). A number of key technologies and equipment have been developed to mitigate outburst risk, including gas drainage from gas-rich zones in the roof of a mined protective seam, gas drainage in de-stressed seams protected which are some distance away from a protective seam, and goaf gas drainage with surface wells. It has been demonstrated in Huainan coalmine that by applying these technologies and equipment, seam gas pressure can be reduced from 4 to 6 MPa (original) to 0.2–0.5 MPa and seam gas content from 13 to 36 m^3/t to about 5 m^3/t. The seam swelling value was increased by 26.33‰, the de-stressing angle of a de-stressed seam was increased by 17°–20°, and the seam permeability was enhanced from 0.01135 to 32.687 m^2/(MPa d) or an increase of 2880 times (Yuan, 2008b, 2009a, 2009b) (Fig. 8).

2.2.3. Integrated pillarless coal mining and gas drainage with a retained goaf-edge gateroad and Y-type ventilation system

In multi-seam mining, a seam of low gas content, low safety risk, and small thickness (0.4–1 m) is selected as a first mining seam. A Y-type ventilation system is employed in the coal seam mining and a retained goaf-edge gateroad is used to drain gas from goaf and other de-stressed seams (Yuan, 2009b; Yuan and Xue, 2013; Xue and Duan, 2014; Zhang et al., 2014), as shown in Fig. 9. The application of this integrated mining method relies on successful development of a number of key technologies and equipment, which includes (1) high-performance cable bolts with steel mesh and grouting (P_1), (2) self-moving secondary support (P_2), (3) sidewall support of a goaf-edge gateroad (P_3), (4) high loading-resistance materials in sidewall filling (quick setting, maximum compressive stress of 28 MPa, compression ratio of 5%), (5) modulated support for sidewall construction (advance rate more than 10 m/d), and (6) gas drainage with boreholes drilled into overlying and underlying seams from a retained goaf-edge gateroad (Fig. 10). With these key technologies and equipment, the concentration of drained gas has increased from 60% to 70–90%, gas drainage ratio was elevated from 60% to 70%, gas pressure in overlying and underlying seams was dropped to 0.2–0.4 MPa, and gas content was reduced to 3–5 m^3/t. The effective de-stressed zone in vertical direction is from upper 150 m–100 m below the first mining seam. In this text, high-purity drainage gas is used as a resource; in this case, the cost of controlling coalmine gas is reduced by more than 50%.

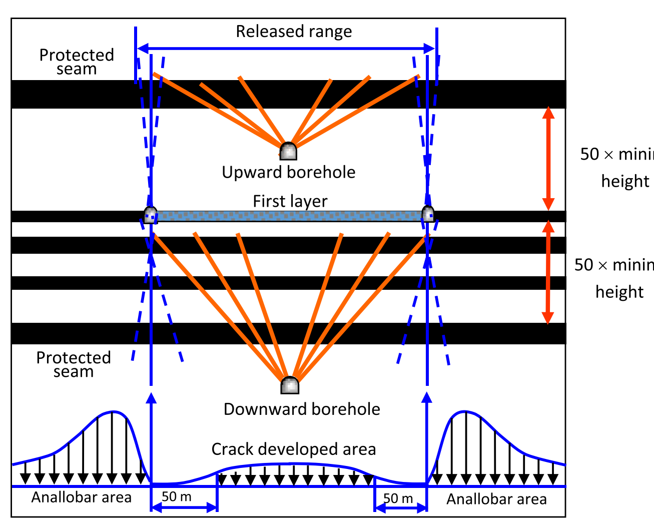


Fig. 7. The principle of gas drainage from de-stressed seams.

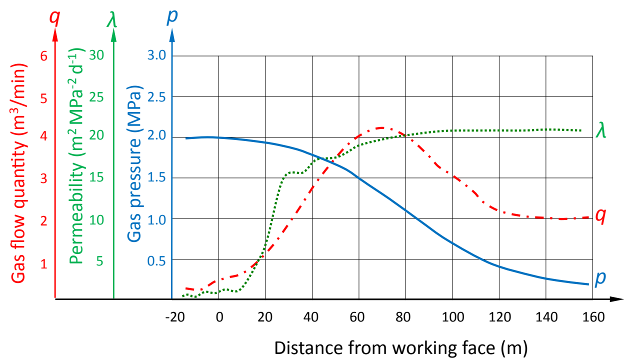


Fig. 8. The performance of gas drainage from de-stressed seams.

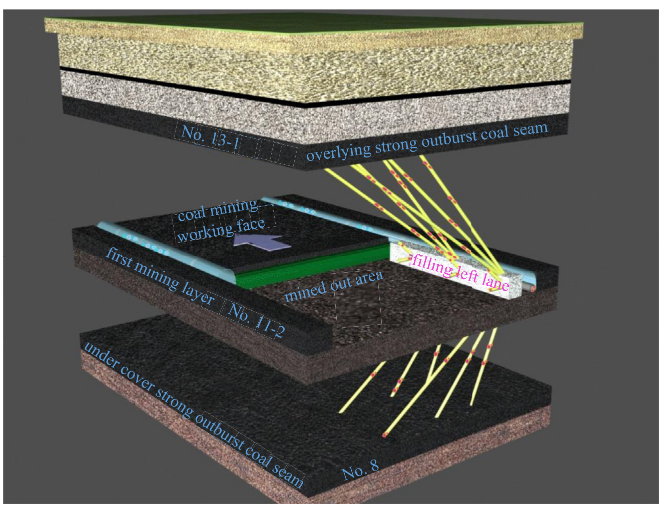


Fig. 9. Integrated pillarless coal mining and gas drainage with Y-type ventilation.

2.2.4. Outburst risk mitigation in mining initial seam through regional stress reduction

The Chinese coalmine safety regulations suggest that regional gas drainage should be adopted to eliminate outburst risk in outburst-prone coalmines. As 80% of mining coal seams in Huainan are outburst-prone, a seam is selected as the initial mining seam to reduce regional stress. To mitigate outburst risk in the first seam mining, some key technologies and equipment were developed, including long-distance horizontal drilling, online borehole deviation monitoring and rectifying system, borehole design and analysis software, hole enlargement by high-pressure water jet, and drilling through faults and the areas of tectonic disturbance (Fig. 11).

2.2.5. Outburst risk mitigation through an integrated approach of both surface and underground gas drainages

Mine layouts and extraction sequence have been integrated with gas drainage from surface and underground to mitigate outburst risk. The de-stressed seam can be the overlying coal seam or the underlying coal seam of the first mining seam. The first mining seam can also be the middle layer of the de-stressed coal seam group. Drilling technology in oil industry has been introduced to Huainan coalmines to improve surface wells for gas drainage purpose in de-stressed seams (Fig. 12). The other technology developments include surface gas well drilling in thick to very thick Tertiary strata of high in situ stress and the multi-purpose of a single gateroad.

2.2.6. Rapid coal sampling from soft coal seams and gas content measurements

Using the theory of outburst prediction with respect to seam gas content, a quick and accurate gas content measurement system has been developed (Fig. 13). In addition, a rapid coal sampling system suitable for deep and soft coal seams has been proposed. The sampling system uses a specially designed double-tubing drilling rod and a reversed circulation of pressurized air to flush sample coal at any given position during borehole drilling (Fig. 14). A coal sample can be taken from an inseam borehole of 85 m long in 5 min, which significantly shortens coal sampling time and reduces

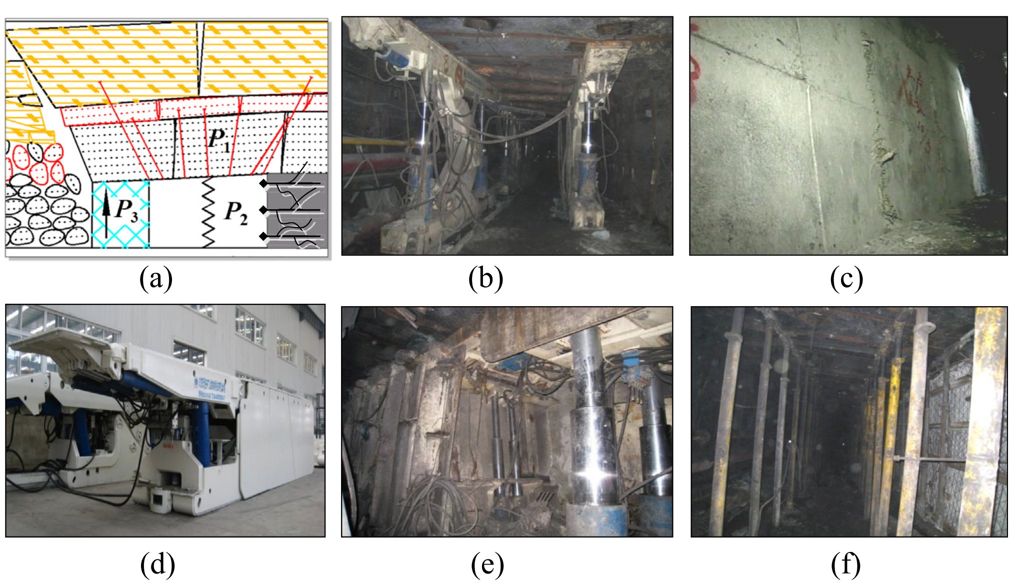
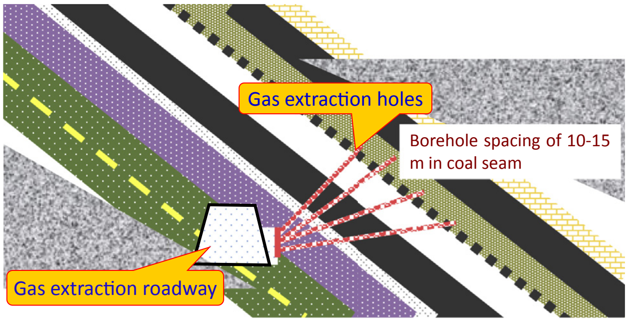
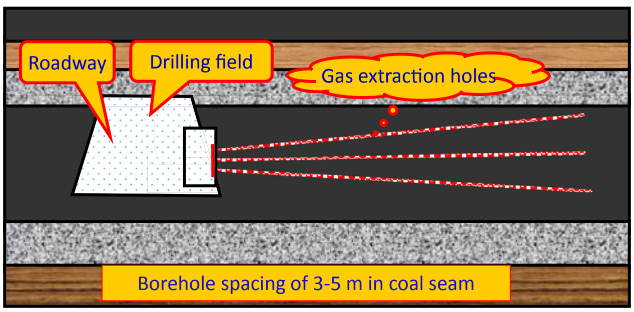


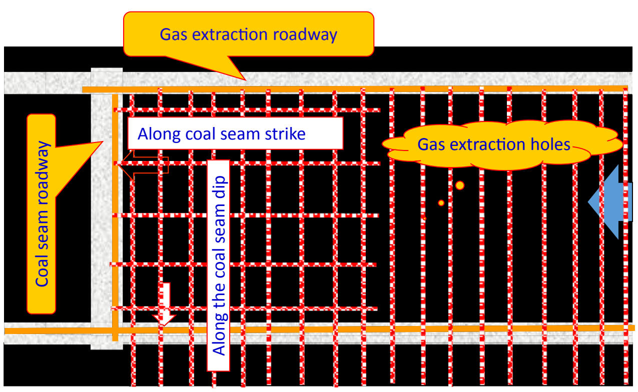
Fig. 10. Strata control with integrated pillarless coal mining and gas drainage. (a) Trinity surrounding rock control technology, (b) Auto mobile assistant enhanced bracket (P_2), (c) Wall filling (P_3), (d) Side formwork bracket for roadside filling, (e) Near template bracket for roadside filling, and (f) Roadway maintenance effect of underground level −900 m.



(a) Cross measure gas drainage from a main gas tunnel.



(b) Inseam gas drainage.



(c) Inseam gas drainage from a main gas tunnel.

Fig. 11. Outburst elimination through regional de-stressing.

sample's "lost gas", and increases the accuracy of gas content measurements (Yuan et al., 2011b; Yuan and Xue, 2014a, 2014b).

2.2.7. Outburst prevention in coal uncovering in rock crosscut development in deep mining

Key technologies and equipment for uncovering coal of low permeability in rock crosscut extraction and shaft in deep coal mining include quick measurement of seam gas pressure, rapid borehole drilling, seam permeability enhancement through borehole flushing with high-pressure water and blasting, pressurized borehole sealing, quick dust reduction at borehole collars, and a device to prevent bursting in borehole drilling (Figs. 15 and 16). The application of these technologies and equipment has mitigated the risk of borehole bursting. As a result, the seam permeability was enhanced by 3–5 times, gas drainage radius was increased from 1.5 m to 3 m, the number of boreholes required for gas drainage was reduced by 60%, drainage gas purity was increased by 40%, and the time required for coal uncovering in rock crosscut development was reduced by 30%.

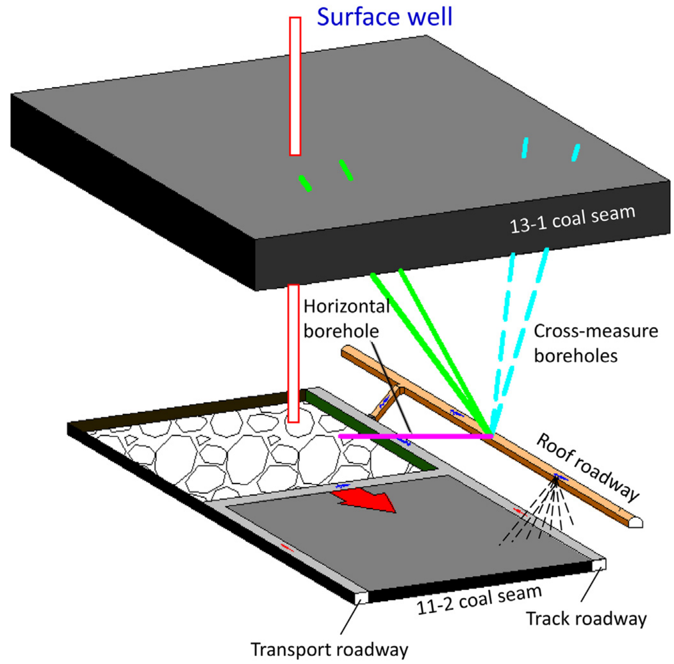


Fig. 12. An integrated approach of both surface and underground gas drainage.

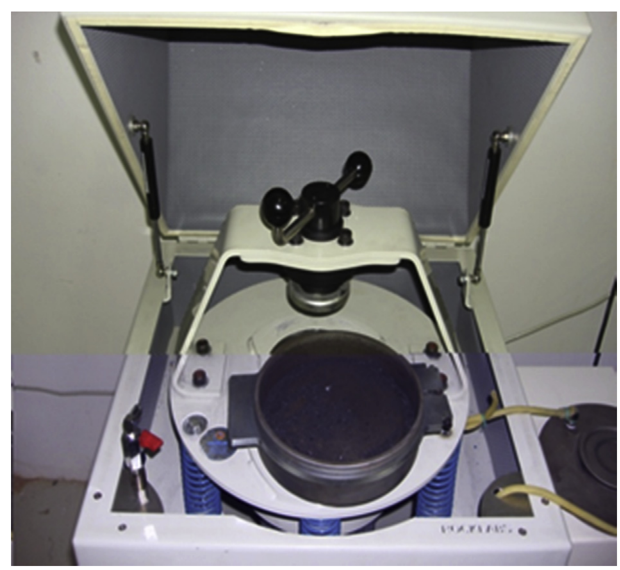
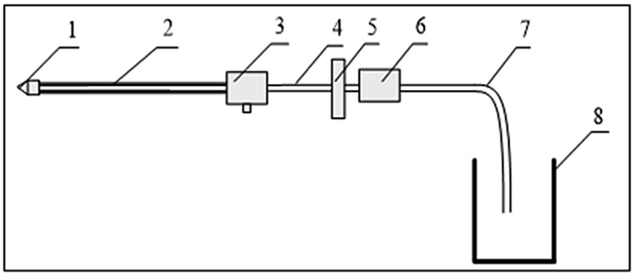


Fig. 13. A coal sample crusher in gas content measurement system.

2.3. Overall performance of outburst control in Huainan

Outburst control in Huainan has been significantly improved as a result of these achievements. From 1996 to 2013, the amount of drainage gas was increased from 10×10^6 m^3 to 590×10^6 m^3, and gas drainage ratio was increased from 5% to 70.5%. No gas exposition occurred. The annual coal production was increased to 71.20×10^6 t, the fatality rate per one million tons of coal production was reduced to 0.07, and the coal resource recovery ratio was increased from 60% to 70%. A number of large, modern, safe, and high-productive coalmines to extract highly gassy coal seams



1-drill bit; 2-compound drill pipe; 3-side-in rotary connector; 4-end-drill pipe; 5-drill chuck; 6-normal incidence rotary connector; 7-sampling hose; 8-sample container

Fig. 14. A schematic of the sampling-while-drilling system.

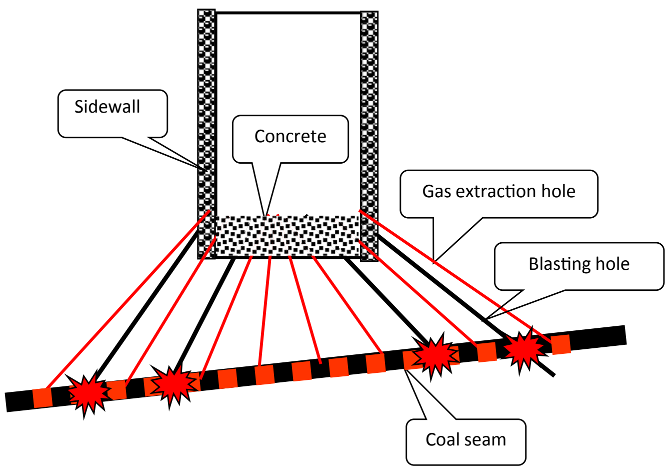


Fig. 15. Outburst prevention in coal uncovering in shaft sinking.

have been constructed and/or in operation. Of these mines, Guqiao and other six mines with annual coal production of (5–10) $\times$ 10^6 t are designated as national demonstration mines for successful mining in highly gassy and deep coal seams with up to 6 $\times$ 10^6 t of coal output per single longwall panel.

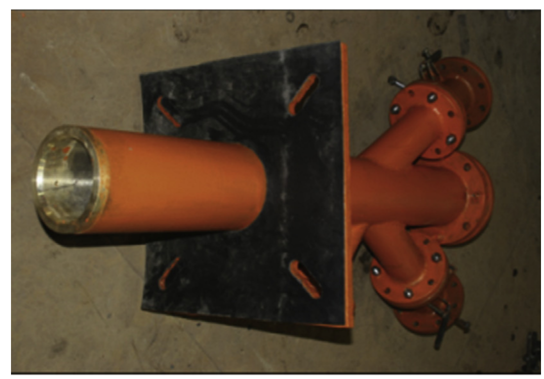
3. Key issues in outburst control

Despite the significant achievements in Huainan, there are still challenging issues for continued improvement in outburst control. The key issues include the lack of theoretical understanding of outburst and its prevention by gas drainage, and the absence of practically effective technologies in outburst risk mitigation in coal seams of soft, deep and low permeability.

3.1. Fundamental theory of outburst indices

Outburst of coal and gas is a very complex dynamic phenomenon, which is considered to be the result of the interaction of multi-factor. Our understanding of coal and gas outburst is still in the stage of qualitative description instead of quantitative analyses. Moreover, there is still no mature theory to describe the mechanisms of its occurrence, initiation, and development. The absence of full understanding of the outburst mechanisms can lead to the limits in outburst control, as the current outburst prediction indices used may have no close relationship with outburst. As mining depth increases, gas-driven outbursts in shallow mining depth may gradually become stress-driven outbursts, rockbursts, or a combination of both.

(a)



(b)

Fig. 16. A device in bursting prevention in borehole drilling.

3.2. Fundamentals in outburst mitigation with gas drainage

Due to the anisotropic nature of coal and rock strata and the non-Darcy flow of gas in coal, fundamental studies on outburst mitigation with gas drainage are merely limited to mathematical analyses, and there is a lack of the support of extensive laboratory and field tests. There are no significant advances in theoretical aspects of gas enrichment and flow in coal seams and surroundings affected by mining. The current theoretical understanding of outburst mitigation with gas drainage has no significant practical guidance in gas emission prediction, gas drainage prediction, and ventilation condition prediction as these predictions are commonly used with empirical data, which are not suitable in practice.

3.3. Outburst mitigation technique in soft coal seam with low permeability

There are constrains with traditional outburst mitigation technologies by gas drainage, as various engineering projects such as extraction of gas drainage tunnels and borehole drilling are of high cost and long drainage duration. In recent years, a number of new gas drainage technologies have been proposed such as surface wells targeting both coal seams and goaf. However, the performances of these technologies are not satisfactory, particularly when they are applied to outburst mitigation in deep and soft coal seams characterized by low permeability. Some technologies require further improvements, including in-situ permeability enhancement, large-diameter surface gas drainage well drilling into deep coal seams, underground directional borehole trajectory monitoring and deviation rectifying system, long-distance directional drilling, drilling through fractured and fragmented coal seams, surface well stability, controlled borehole drilling and hydro-fracturing in closely spaced multi-seam (seam interval of 2–5 m), and gas drainage in mining spontaneous combustion-prone seams.

4. Strategies in outburst control

4.1. Outburst mechanism, control technologies and equipment

An investigation should be conducted through extensive physical simulations of outbursts in coal extraction and coal uncovering in rock crosscut development. With the large-scale outburst physical modeling system, the real-time data acquisition of field monitoring, testing, and numerical modeling can then be realized. The investigation should focus on the dynamic process of outburst occurrence, initiation and development, and it can capture any precursor prior to outbursting. This will lead to establishment of outburst prevention systems and associated outburst control technologies and equipment.

4.2. Gas drainage and its effect on outburst risk mitigation

Studies should concern the fundamental understanding of drainage gas flow in deep and anisotropic coal and rock strata. In this regard, the characteristics of gas enrichment and gas flow in coal seams and surroundings under various mining and gas drainage conditions can be understood. Moreover, gas flow mathematical models that can take into account the coupling effects of stress field, fracture field, and gas field should be established. Thus, accurate prediction for gas-rich zones, gas emission, and gas drainage should be implemented. The mechanism and model of combined gas drainage from surface and underground gas drainage in association with high efficient gas drainage methods in coal seams of low permeability should be developed in order to provide scientific guidance for gas drainage in deep coal seams.

Key technologies and equipment include (1) large-diameter surface wells of over 1000 m in depth, (2) long-horizontal boreholes with multiple branches, (3) underground directional borehole trajectory monitoring and deviation rectification system, (4) underground long-distance (about 1000 m) and large-diameter (ϕ200 mm) directional drilling, (5) directional drilling in soft and deep coal seams (about 250 m borehole in length), (6) underground borehole drilling with surface-based operation control of automatic movement, positioning, rod shuffling, and (7) setting borehole angles between -20° and 60° in relation to seam dip.

4.3. Coal seam permeability enhancement

To enhance the permeability of deep and soft coal seams of high in-situ stress and gas content, a variety of technologies and equipment need to be developed. These include water flushing of boreholes, hydro-fracturing of surface wells in closely spaced coal seams, water jet slotting, powerful repetitive impulse wave, controlled blasting of boreholes with high pressure CO_2, staged fracturing of horizontal boreholes, response of a special coalfield, tight radius drilling, and cavity creation with high pneumatic pressure. These developments can facilitate the seam permeability enhancement and increase gas drainage efficiency under various mining and geological conditions.

4.4. Integrated coal mining and gas drainage in deep multi-seam hazards control

Detailed studies should be focused on the deformation and damage mechanism of the surrounding rocks of a gateroad under high in-situ stress mining conditions, and on the dynamic interaction among stress field, fracture field and gas field in the process of integrated coal mining and gas drainage. The studies should also illustrate the principle of gas drainage layouts, strata control, and high efficient gas drainage. Furthermore, physical simulations should be conducted to model first seam mining with the large-scale, and truly triaxial system should be implemented for integrated coal mining and gas drainage in order to understand dynamic development of stress, fracture and gas fields in roof and floor strata, and to identify gas-rich zones subsequently.

More studies should be concentrated on the improvement of drilling in soft and fragmented coal seams, drilling through goaf areas into underlying seams, borehole stability, damage to gas drainage pipelines due to coal dust bursting from boreholes, and damage to borehole casing due to strata compression and shearing resultant from overburden movement.

For gas drainage in spontaneous combustion-prone seams, studies should be concerned on development of a monitoring system for multi-gas parameters related to both gas drainage and coal spontaneous combustion. An intelligent control device enabling simultaneous operations of intensive gas drainage and nitrogen injection for fire prevention is needed. With the system and device in hand, both gas and spontaneous combustion hazards can be effectively controlled.

5. Concluding remarks

Significant developments in the basic theory, key technology and equipment of outburst prevention and control are observed in recent years in China. These achievements have effectively used to prevent coal and gas outburst accidents, but the coal and gas outburst prevention is still one of the most challenging issues in coalmine. Under these difficult geological conditions, gas and coal outburst control must take a combination approach of both regional and localized preventions. Other principles of outburst control include the use of non-outburst seams to protect outburst seams, less outburst-prone seams to protect strong outburst-prone seams, de-stressing prior to mining, a combination approach of both surface and underground gas drainage or “a two-legged approach”. In the future, we have to undertake fundamental research on outburst mechanism, outburst control technologies and equipment, and to carry out green and intelligent mining for the purpose of safe and efficient coal mining of deep coal resources.

Conflict of interest

The author wishes to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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