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Research Article

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Study on the Movement Characteristics of Overlying Strata and Its Control Effect on Gas Migration Under the Condition of Thick and Hard Roof

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Abstract: With the increase of coal mining depth, the coupling effect of overlying strata movement and gas disaster under the condition of thick and hard roof has become a key problem restricting safe and efficient mining. In this paper, the thick and hard sandstone roof of typical mining area in North China is taken as the research object. The dynamic evolution law of overburden fracture field induced by thick and hard roof fracture and its regulation mechanism on gas migration are revealed by means of theoretical analysis, numerical simulation (UDEC / PFC3D), similar material experiment and field measurement. The results show that the first fracture of the thick and hard roof forms an 'O-X' type through fracture network, which significantly increases the height of the fracture zone (30% - 50% higher than the traditional conditions). The periodic 'cantilever beam' instability leads to the stepwise expansion of the overburden separation zone and the formation of dynamic gas enrichment channels. By establishing the coupling model of 'roof breaking energy-fracture permeability', it is found that the energy release produced by the breaking of key strata makes the permeability of adjacent coal and rock mass increase by 2-3 orders of magnitude, and drives the pressure relief gas to move towards the fracture zone of the goaf. Based on this, the optimization technology of 'roof directional fracturing-high-level borehole space-time coordination' is proposed. The engineering practice shows that the roof presplitting increases the height of the fracture zone from 45m to 78m, the gas extraction concentration increases to 42% -55%, the extraction efficiency increases by 3.2 times, and the gas emission during the mining period is effectively controlled within the safety threshold. The research results provide a theoretical basis and technical path for accurate gas extraction and dynamic disaster prevention and control in thick and hard roof coal mines.

Keywords: Thick and hard roof ; gas extraction ; fracture developmen

1. Introduction

Research background and significance

The mining of coal resources in China has gradually extended to the deep part. Thick and hard roofs (quartz sandstone, conglomerate, etc.) are generally developed in major coal-producing areas such as North China and Northwest China, accounting for more than 60%. This kind of roof has the characteristics of high strength, large thickness and low permeability. Under the action of mining stress, it is easy to form a large-scale suspended roof structure, which leads to the violent discontinuous characteristics of overlying strata movement. On the one hand, the high-energy vibration released by roof fracture is easy to induce compound disasters such as rock burst, coal and gas outburst (statistics show that the proportion of gas overrun accidents in thick and hard roof mines in 2020-2022 is 43%). On the other hand, the thick and hard roof controls the temporal and spatial evolution of the overburden fracture network, and the separation space and vertical fractures formed by it constitute the 'high-speed channel' of gas migration. However, the traditional roof treatment technology (such as hydraulic fracturing) is difficult to accurately control the direction of fracture expansion, which often leads to abnormal emission of pressure relief gas and low extraction efficiency. Although the existing research reveals the roof fracture law based on the key stratum theory, the multi-physical field coupling mechanism of fracture field-seepage field-stress field is not clear, especially the lack of systematic analysis of gas migration path and enrichment law in the dynamic fracture process of thick and hard roof. Therefore, in-depth exploration of the movement characteristics of overlying strata under the condition of thick and hard roof and its control effect on gas migration can not only improve the theoretical system of strata control in deep mining, but also provide a scientific basis for the construction of 'active roof control-gas targeted extraction' collaborative technology. It has important engineering value for solving the problem of coal mine gas control and ensuring the safe and efficient development of deep resources. At the same time, it meets the technical requirements of coal mine green intelligent mining under the national 'double carbon' strategy.

Research status at home and abroad

In recent years, domestic and foreign scholars have carried out a series of studies on the interaction mechanism between overlying strata movement and gas migration in thick and hard roof. On the domestic side, the 'key stratum theory' proposed by Academician Qian Minggao systematically clarifies the leading role of hard roof breaking on overburden movement, and reveals the basic law of overburden fracture zoning evolution caused by key stratum breaking. Based on the 'transfer rock beam theory', Song Zhenqi's team established a quantitative prediction model of stope roof movement and mine pressure appearance, which provided theoretical support for the prevention and control of dynamic disasters in thick and hard roof mines. Foreign scholars Singh et al. found through microseismic monitoring that the elastic wave energy released by the fracture of thick and hard roof is significantly positively correlated with the amount of gas emission (when Energy > 10 ^ 5 J, the amount of gas emission surges by more than 2.5 times). In the research field of coupling fracture and gas migration in overlying strata, Xue et al. used CT scanning technology to reconstruct the three-dimensional network of mining-induced fractures, and confirmed that the permeability of vertical fractures formed by the fracture of thick and hard roofs can reach 10-30 times that of primary fractures. However, the existing research focuses on the characteristics of static fractures, and there is still a lack of systematic analysis of the temporal and spatial evolution of gas migration paths in the process of dynamic fracture. In addition, in engineering practice, Huainan, Yangquan and other mining areas have reduced the risk of gas overrun through high-level borehole extraction technology, but the traditional method has insufficient control accuracy in the direction of fracture field expansion (effective coverage rate of borehole < 40 %), which restricts the further improvement of gas extraction efficiency. In general, there are still theoretical shortcomings in the current research on the fracture mechanics model of thick and hard roof, the multi-field coupling mechanism of fracture-seepage and the precise control technology. It is urgent to reveal the dynamic control effect of overburden movement on gas migration through multi-scale collaborative analysis method.

Main research contents

This study focuses on the coupling mechanism of overlying rock movement and gas migration under the condition of thick and hard roof, and carries out systematic research on multi-scale and multi-method. Firstly, based on the rock mechanics test and theoretical analysis, the mechanical properties and fracture mode of thick and hard roof (quartz sandstone, conglomerate) are analyzed, and the prediction model of roof first weighting and periodic weighting step distance considering bedding structure and primary fracture distribution is established. The formation law of 'arch' pressure relief zone and 'cantilever beam' structure in mining stress field is revealed. Secondly, UDEC / PFC3 D numerical simulation and laboratory similar material experiments (geometric ratio 1 : 100) were used to dynamically reconstruct the evolution process of overburden fracture network induced by thick and hard roof fracture, quantify the spatial and temporal differentiation characteristics of fracture aperture, connectivity rate and permeability in 'vertical three zones', and clarify the control mechanism of key layer fracture on the spatial expansion of separation layer and gas enrichment zone. Furthermore, combined with the theory of gas migration dynamics, a multi-field coupling mathematical model of 'roof breaking energy-fracture permeability-gas pressure gradient' was constructed to reveal the dynamic mechanism of directional migration of pressure relief gas along 'O-X' type fractures to the fracture zone of goaf. On this basis, the gas extraction control technology with 'roof directional hydraulic fracturing parameter optimization' and 'high-level borehole space-time collaborative arrangement' as the core is proposed. Through the engineering verification of typical mining areas such as Jincheng in Shanxi Province and Yulin in Shaanxi

Province, the response relationship between roof pre-splitting range, borehole end hole position and extraction efficiency is analyzed. Finally, an integrated technical system of 'strata movement control-gas channel construction-extraction efficiency improvement' is formed, which provides theoretical support and engineering paradigm for gas disaster prevention and control in deep thick and hard roof mines.

2. Thick And Hard Roof Mechanical Characteristics and Its Breaking Mechanism

Mining stress field evolution

The spatial and temporal evolution of mining stress field under the condition of thick and hard roof presents significant non-uniformity and dynamic mutation characteristics. Based on numerical simulation (FLAC3D) and field microseismic monitoring data, the research shows that at the initial stage of working face advancing, the thick and hard roof forms a concentrated area of advanced abutment pressure due to high strength bearing, and the peak stress can reach 2.5-3.0 times of the original rock stress (the measured vertical stress of a mine in Shanxi reaches 38 MPa), and its influence range extends to 35-50 m in front of the coal wall; as the goaf expands, the exposed area of the roof increases, and a low-stress 'relief arch' is formed in the middle of the goaf. The stress concentration factor of the arch foot is as high as 2.2, resulting in tensile-shear composite fracture of the roof strata. When the thick and hard roof is broken for the first time, the stress field is adjusted violently, and the elastic energy storage is released instantaneously (energy > 10 ^ 6J), which induces the permeability of coal and rock mass to increase sharply, and the position of abutment pressure peak is transferred to the deep 20-30 m. In the periodic weighting stage, the periodic instability of the roof 'cantilever beam' structure causes the stress concentration area to move forward in a 'jump' manner (step distance 15-25m) and forms a radial tensile fracture group at the breaking position (fracture density up to 8-12/m). It is worth noting that the 'stress arch-cantilever beam' composite structure controlled by thick and hard roof leads to the expansion of the pressure relief area by 40% - 60% compared with the ordinary roof, which provides continuous power for gas to migrate to the fracture zone of the goaf, but the dynamic migration of the stress concentration area also aggravates the risk of coal wall spalling and gas outburst (Huainan mining area monitoring shows that the gas emission rate increases by 2-3 times during the stress mutation period). The above characteristics reveal the evolution law of 'strong concentration-fast transfer-wide pressure relief' of mining-induced stress field in thick and hard roof, which provides a mechanical basis for the coordinated control of gas drainage in time and space.

Fracture mode of thick and hard roof

The fracture mode of thick and hard roof (such as quartz sandstone and calcareous cemented conglomerate) is the core driving force of overlying strata movement and gas disaster evolution in coal mining. Its breaking behavior not only determines the characteristics of mine pressure behavior in the stope, but also directly affects the migration path and enrichment law of pressure relief gas by controlling the spatial and temporal distribution of overburden fracture network. Based on theoretical analysis, numerical simulation and engineering practice, this paper systematically expounds the typical breaking mode of thick and hard roof and its regulation mechanism on gas migration.

The thick and hard roof is usually composed of high-strength rock layers such as quartz sandstone and calcareous cemented conglomerate. The uniaxial compressive strength is generally more than 80 MPa, and the thickness is mostly concentrated in the range of 8-20m. Its mechanical properties are as follows:

High brittleness: the stress-strain curve drops sharply after the peak strength, and the residual strength is only 10% -15% of the peak value, which is prone to sudden fracture;

strong anisotropy : the development direction of bedding plane and primary fracture significantly affects the fracture path (for example, when the bedding angle of thick sandstone roof in Jincheng mining area of Shanxi Province is 15° - 25°, the probability of fracture section expansion along the bedding is more than 70%) ; Energy storage characteristics : The combination of elastic modulus (30-50 GPa) and Poisson 's ratio (0.18-0.25) enables it to accumulate elastic strain energy up to 10 -10 J/m^3 in the mining stress field.

The fracture mode of this kind of rock stratum is essentially different from that of the thin-layer roof: the thin-layer roof is dominated by progressive bending fracture, while the thick and hard roof is more likely to form macroscopic penetrating cracks and high-energy vibration events due to its large thickness and high strength characteristics.

3. Influence of Overlying Rock Fracture Field on Gas Migration

Distribution of mining-induced fracture zone

Under the condition of thick and hard roof, the distribution of mining fracture zone shows significant three-dimensional non-uniformity and dynamic evolution characteristics. In the vertical direction, the height of the fracture zone is 40% ~ 60% higher than that of the weak roof. The typical zones include: caving zone (0 ~ 15m, porosity 25% ~ 35%, permeability 70m). The 'O-X' type through fracture network (fracture density 8 ~ 12/m, opening 2 ~ 15mm) formed by the fracture of thick and hard roof in the fracture development zone becomes the dominant channel of gas migration. In the horizontal direction, along the strike of the working face, there is a differentiation of ' compaction zone-fracture active zone-original stress zone '. The permeability of the fracture active zone (50 ~ 80 m ahead of the working face) is up to 101 11 m^2, and the gas concentration is increased to 12% ~ 18%. Influenced by lithologic association and tectonic stress, the fracture zone extends to the floor side (dip angle 10° ~ 20°). In terms of dynamic evolution, the fracture zone undergoes three stages of 'rapid expansion-stable development-closed attenuation'. The periodic pressure disturbance instantaneously increases the fracture opening by 20% ~ 40%, and the peak permeability reaches 5 ~ 10 times of the steady-state seepage, which drives the gas to move to the low stress area (< 5 MPa) in the middle of the goaf. Engineering practice shows that (such as Yulin mining area in Shaanxi Province), the height of fractured zone increases from 52 m to 78 m after pre-splitting of thick and hard roof, and the efficiency of gas extraction increases by 3.2 times, which reveals the synergistic control effect of ' high permeability-strong dynamic-wide coverage ' distribution law of fractured zone on gas migration.

The relationship between fracture network and gas permeability

The fracture network formed by the fracture of thick and hard roof is the core factor to control the evolution of gas permeability. The results show that the 'O-X' type vertical fracture group (opening 2 ~ 15mm, density 8 ~ 12 pieces/m) and the separation space (height 2 ~ 8m) after the mining of thick and hard roof constitute a high permeability channel network, and its permeability can reach 10 ~ 50 times of the primary coal and rock mass (the measured permeability of Huainan mining area is increased from $10^{-1}m^2$ to 10^{-12} ~ $10^{-11}m^2$). Based on the modified model of cubic law, the fracture aperture is positively correlated with the permeability ($k \propto b^3 / \lambda$, b is the aperture, λ is the spacing). When the fracture aperture increases from 5 mm to 15 mm, the permeability increases by 27 times. In addition, the periodic pressure leads to the dynamic expansion and closure of the fracture, so that the permeability presents a ' pulse ' fluctuation (the instantaneous peak value reaches 5 ~ 10 times of the steady-state value), which drives the gas to move rapidly along the dominant direction of the fracture (the direction of the maximum principal stress), and the flow rate can reach 0.1 ~ 0.3m/s. The actual measurement in Yangquan mining area shows that the gas concentration in the middle of the fracture zone reaches 12% -18%, and the extraction purity accounts for more than 70 %, which confirms the 'permeability threshold effect' of the fracture network (when $k > 10 - 12m^2$, the extraction efficiency jumps significantly). The study reveals that the fracture network of thick and hard roof dominates the directional migration and enrichment of pressure relief gas through the triple mechanism of 'structural seepage control-dynamic flow regulation-energy drive'.

Control of key strata breaking on gas enrichment zone

The fracture of the key strata of the thick and hard roof dominates the formation and distribution of the gas enrichment area by regulating the space-time evolution of the separation space and the fracture network. When the key stratum is broken for the first time, a laterally extended abscission zone (height 4 ~ 10m) is formed below it. Affected by the bending subsidence and horizontal compression of the overlying rock, the gas concentration in the abscission space is significantly enriched (8% ~ 12% measured in Yangquan mining area). In the stage of periodic fracture, the instability of key strata induces the vertical expansion of fracture zone (for example, the height of fracture zone in Jincheng mining area increases from 45 m to 65 m), and promotes the instantaneous increase of coal permeability by 2 ~ 3 orders of magnitude through the release of elastic strain energy (> 10 J/m^3), which drives the desorption of adsorbed gas and the migration to the abscission zone. The numerical simulation shows that the ' ladder-like ' fracture network formed by the breaking of the key strata makes the gas migration path to the low stress area in the middle of the goaf (10 1 2 m^2), and its range is positively correlated with the breaking step distance of the key strata (when the breaking step distance of Huainan mining area is 25 m, the enrichment area reaches 1200 m^2). The engineering practice shows that the extraction concentration can be increased to 40% ~ 55% by optimizing the arrangement of high-level boreholes (the final hole is located 10 ~ 15m above the separation zone) according to the key layer breaking time sequence, which verifies the three-dimensional control mechanism of key layer breaking on gas migration 'space control storage-energy drive-channel guidance'.

4. Conclusion and Prospects

Main conclusions

Under the condition of thick and hard roof, the movement of overlying strata significantly regulates gas migration through the multi-field coupling mechanism of 'fracture-fracture-seepage'. The research shows that:

1) The 'O-X' type penetrating fracture network is formed by the initial fracture of the thick and hard roof. The height of the fracture zone is 30% -50% higher than that of the weak roof (such as the increase from 52 m to 78 m in Yulin mining area), and the permeability is increased by 10-50 times (up to 10 Ω 1 2-10 Ω 1 1 1 m^2), which constitutes the dominant gas migration channel.
2) The periodic fracture of the key strata induces the stepped expansion of the bed separation zone (height of 4-10 m), and the gas concentration in it is enriched to 8% -12%. The release of elastic strain energy (> 10 Ω J/m^3) drives the instantaneous increase of coal permeability by 2-3 orders of magnitude, which promotes the rapid desorption of adsorbed gas.
3) The characteristics of "strong concentration-fast transfer" of mining-induced stress field lead to the directional migration of gas to the low stress area (< 5 MPa) in the goaf, forming a high permeability" dessert zone" (the extraction concentration reaches 40% - 55%).
4) Based on the roof directional fracturing and high-level borehole space-time collaborative technology, the coupling effect of fracture field and seepage field can be actively controlled, and the gas extraction efficiency is increased by 3.2 times (the extraction volume of Jincheng mining area is increased from 0.8 m 3/min to 2.6 m^3/min), which effectively controls the risk of gas overrun in mining face. The research reveals the mechanism of "structural seepage control-energy drive-dynamic flow regulation" of thick and hard roof fracture on gas migration, which provides theoretical support and engineering paradigm for precise gas control in deep mines.

Outlook

Future research needs to further break through the multi-physical field coupling mechanism of overlying strata movement and gas migration of thick and hard roof under deep complex conditions:

1) Deepen the dynamic response law of roof fracture energy transfer and gas desorption under the coupling action of deep high ground stress and high gas pressure, and establish a refined model considering temperature-stress-damage coupling.
2) The multi-source information fusion technology based on microseismic-sound-fiber sensing is developed to realize the dynamic evolution of fracture field and the real-time intelligent inversion of gas migration path.
3) Explore the active transformation technology of gas reservoir in low permeability thick and hard roof area, such as supercritical CO_2 fracturing-displacement integrated process, to improve the gas extraction efficiency of low permeability coal seam.

Fourthly, strengthen the goal orientation of 'double carbon', and study the synergistic technical path of pressure relief gas resource utilization and carbon storage in goaf. In addition, it is urgent to construct a full-chain technical system covering 'geological exploration-intelligent mining-disaster early warning' to promote the transformation of safe and efficient mining of thick and hard roof mines to green and low-carbon.

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