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Editorial

Advances in mining safety theory, technology, and equipment

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Abstract:
Mineral resources are increasing important for sustainable development in modern society. As the progressive depletion of shallow mineral deposits, deep or ultra-deep mineral extraction is an inevitable choice for mineral and energy security in various countries in the future. The trend of occurrences of geohazards including rock burst, cascading ground failure, uncontrollable underground space squeezing, coal and gas outburst, and fires, will be expected to excessively increasing as deepening the mine depth. Mining safety science and engineering challenges are drawing more and more attention over last decade and beyond. In August 2023, the 6th International Symposium on Mine Safety Science and Engineering was held in Harbin to promote innovative development of mining safety, and foster international collaborations among scholars in the field of mining safety. It served as a platform for the exchange of the most recent advancements in mining safety scientific theories, technologies, and equipment by bringing together global talent. Over 400 attendees representing 9 countries, including Australia, Russia, United State, Kazakhstan, and Canada, engaged in academic discussions and knowledge sharing on new theories, technologies, equipment, and methods in mining safety science and engineering. The latest research results are of great significance in enhancing the practices of preventing mine disaster and ensuring the safety of mining operations.

1. Introduction

Mineral resources are widely distributed across the globe, and both businesses and governments place a significant emphasis on ensuring safety in mining operations (Hosseini, 2017; He et al., 2021). With the increase of mining depth, mines are facing complex production environments such as high ground stress, high geothermal temperature, high rock saturation water pressure, and strong dynamic load disturbance (He et al., 2005, 2018; Zhu et al., 2018). Further research is urgently needed on the mechanisms of deep rockburst, coal and gas outburst, mine fires, and technologies of monitoring and preventing these hazards (Kaiser and Cai, 2013; Lin et al., 2015; Konicek et al., 2019; Vennes et al., 2020; Lu et al., 2022). The latest research mainly focuses on the fundamental theory of deep mine disasters and monitoring and control technologies, especially on issues related to complex disaster mechanisms and intelligent monitoring technologies (Pu et al., 2018, 2019; Małkowski and Niedbalski, 2020; He et al., 2023). In this context, the International Committee on Mine Safety Science and Engineering (ICMSSE) provides an international academic exchange platform for global scholars to focus on the innovative development of global mine safety science and engineering, allowing them to exchange new theories, technologies, and engineering practices in mine safety science, promoting interaction between governments, enterprises, and academia. Since 2011, the ISMSSE has

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successfully organized five conferences in China, Canada, and Poland, making important contributions to promoting the development of mine safety. During August 18-20, 2023, the 6th ISMSSE was held in Harbin. The research topics covered in this workshop are summarized as follows.

2. Mechanism, monitoring and prevention technology of rockburst

With the increase of mining depth and intensity, rockburst hazards are becoming increasingly serious. Innovative development of mechanism, monitoring and prevention technologies of rockburst are of great significance in reducing disaster occurrence. In the presentation entitled "Ground control challenges in underground mines" by Ismet Canbulat, from the University of New South Wales, he introduced ground support design for both static and dynamic loading environments based on the safety records of the Australian longwall mining method and the Plan-Do-Check-Act strategy. To enhance the accuracy of coal burst and outburst assessments, a time-dependent support coupling model was proposed, utilizing a combination of analytical models, numerical models, and empirical models.

Rasskazov Igor, from Khabarovsk Federal Research Center of the far eastern branch of the Russian Academy of Sciences, gave a presentation on "Methods, technical means and results of the rockburst hazard study in underground mining of ore deposits". He developed an advanced automated monitoring system for geomechanics to evaluate the risk of rockburst in underground mining. The system has multiple functions such as geodynamic zoning of the mine field, seismic-acoustic activity parameters. By utilizing this system, the potential areas prone to rockburst in mines were accurately identified.

Yizhuo Li and Hani Mitri, from McGill university, delivered a lecture entitled "Mining face stability assessment in hard rock mining: A case study". They demonstrated a new method for evaluating the stability of the working face by conducting diametrical core deformation technique on a few core rock samples to predict the local stress field near a face. The result of diametrical core deformation technique is effective to use for local field stress prediction with numerical modelling.

Linming Dou, from the China University of Mining and Technology, delivered a talk entitled "Compound hazard of rock-burst & roof-fall in coal mine". During the presentation, he conducted a thorough analysis of the similarities and differences between roadway roof falls and rockburst incidents. Additionally, he clarified the distinct characteristics of the compound hazard resulting from the simultaneous occurrence of rockbursts and roof falls. Subsequently, he delved into the damage process, identified the influencing factors, and elucidated the fundamental causes of this composite disaster. Lastly, an effective control strategy aimed at mitigating the compound hazard of rockbursts and roof falls was proposed, highlighting its potential for significant control effectiveness.

The development direction of rockburst monitoring and early warning is to adopt a variety of prediction technologies, methods and indicators for comprehensive and automatic monitoring and early warning. Enyuan Wang, from the China University of Mining and Technology, delivered a lecture entitled "Method and platform for risk management and control of rockburst in coal mines and application". A cloud platform-based big data monitoring, analysis and early warning system for mine rockburst risk is proposed, and a hybrid cloud architecture is used to establish a mine rockburst disaster big data monitoring and early warning cloud platform, which realizes a single and multiple coal mines in a region. The functions of impact-related big data analysis, hidden danger identification, risk classification early warning, safety and risk hidden danger information dynamic "one map" and alarm information classification push have been verified and applied.

In the invited talk entitled "Cyclic moisture induced mudstone rock softening and their implications on time-dependent strength reduction and long-term mine roof stability", Shimin Liu, from The Pennsylvania State University, presented the shale and mudstone mine roof deterioration mechanism due to the fluid-shale interactions and cyclic loading. Liu's team experimentally investigated the water vapor retention and migration behavior in shale and coal and established the time-dependent Rock-Fluid Geomechanics Model (TD-RFG Model) to evaluate the evaluate the time-dependent rock structure dynamics. The interactions across the elastic deformation field, the transient fluid transport field and the discontinuous damage field are analyzed and modeled using TD-RFG. And found that both surface chemistry and pore structure determine the water adsorption behavior. The results from experimental work and modeling can ultimately provide the approach for quantifying and evaluating the water retention behavior and suction potential in an unsaturated air-water-shale/coal system and define strategies for ground control.

In the talk on "Integrating geophysics and safety science for dynamic disasters in complex mining environments", delivered by Majid Khan, from the University of Science and Technology Beijing, highlighted that the essential reason for the uneven distribution of microseismicity and rockbursts is the uneven distribution of geological structures and mining stresses. By quantitatively studying the spatial and temporal variations of parameters about the source parameter averages, variation in seismological parameters, maximum potential magnitude, he developed the rockburst hazard assessment and prediction method, which described the sharp increase in the number of microseismic events and elastic energy along with the rapid decrease in seismic parameters as one of the effective precursor indicators of rockbursts.

In the talk "Improvement of hardware and software-methodical means of express-assessment of burst-hazard during underground mining", given by Andrey Alexandrovich Tereshkin, from Mining Institute, Far Eastern Branch of the Russian Academy of Sciences, a new portable device called "Prognoz-L2" was introduced, which designed for local control and assessment of rockburst hazard category. It was developed using state-of-the-art components and advanced microprocessor technologies. The conducted tests demonstrated the device's high level of preparedness, stability, and reliability.

Dazhao Song, from the University of Science and Technology Beijing, delivered a lecture entitled "Coupling generation

mechanism of electromagnetic radiation and micro-vibration induced by coal-rock fracture", found that there is a strong time-frequency coupling relationship between electromagnetic radiation and micro-vibration signals generated from coal-rock fracture. The correlation between electromagnetic radiation and micro-vibration has been confirmed by the changes in surface morphology, micromechanics, and electromagnetic parameters during the loading process at micro and nano scales. He proposed the hypothesis that electromagnetic radiation is generated by coupling effect of charged crack vibration. On the basis of analyzing the strong correlation between electromagnetic radiation and micro-vibration, he developed a new electromagnetic radiation vector-vibration coupling monitor, which helping to improve the level of intelligent monitoring and warning.

In the lecture of "Prediction and prevention of rockburst hazard in Nikolayevskoye deposit of deep-seated polymetallic ores with a complex tectonic structure", given by Potapchuk Marina Igorevna, from Institute of Mining of the Far Eastern Branch of the Russian Academy of Sciences, the block structure, modern geodynamic zoning, and acoustic response characteristics before and after earthquakes of the nikolayevskoye deposit was discussed. Then he conducted numerical simulation research on the distribution and evolution of stress field after mining in multiple areas, and identified potential rockburst risk areas in the rock mass.

The rockburst early warning capability of the multi-parameter integrated system is significantly better than that of a single warning system. Shengquan He, from the University of Science and Technology Beijing, delivered a talk on "Multi-parameter integrated early warning model and an intelligent identification cloud platform of rockburst". He proposed some new early warning indices of rockburst such as cluster degree and energy density, established a multi-parameter integrated early warning model. A cloud platform for remote intelligent assessment of rockburst risk is developed, which effectively improved the timeliness and accuracy of early warning for rockburst.

In "Mechanism of rockburst induced by far-field vibration and control measures", given by Xuelong Li, from the Shandong University of Science and Technology, he developed a rockburst resonance model and a "volume-region-system" rockburst model. An in-depth analysis of the "four-in-one" multi-stage pressure relief prevention and control measures for rockbursts was provided, along with a discussion on the design concept and setting principles of system support. These comprehensive insights contribute to the advancement of understanding and addressing rockburst incidents effectively.

In the presentation on "Research status and bedding effect of coal bursting liability classification", given by Chao Wang, from the Kunming University of Science and Technology, the relevant regulations, influencing factors, and evaluation index classification of domestic rockburst were summarized. He used the PFC3D to study the failure mode and crack propagation distribution of specimens with different inclination angles under different impact strengths. He found the bursting liability coal has different degrees of bedding effect, and when carrying out the identification of the bursting liability grade, the influence of bedding and its angle should be considered.

In the presentation "Physical principle and equipment application of controlled stress wave excitation", given by Chunyang Cui, from China Coal Research Institute, a highly reliable and accurate discrete beam-string model for calculating the generated random striker outlines of the waveforms were proposed. To enhance the prediction accuracy of non-constant expectation sets, he introduced a phase correction approach based on nominal wave velocity, as well as a recurrent neural network training scheme. The application of these proposed methods showcased remarkable improvements in prediction accuracy.

3. Mechanism, monitoring and prevention technology of coal and gas outburst

Coal and gas outburst is one of main disaster in coal mine, usually cause serious economic and social problems. In this section, eighteen researchers induced current progress for the mechanism, monitoring and prevention technology of coal and gas outburst.

Yueping Qin, from the China University of Mining and Technology (Beijing), delivered a talk on "A new numerical calculation method of gas flow model and gas permeability coefficient in single-porosity coal seam". He pointed out the problems existing in the test calculation of the permeability coefficient of coal seams: the relationship between gas content and pressure was oversimplified, which caused serious errors in the gas flow equation. He calculated the gas content by Langmuir formula, took the product of adsorption constant b and pressure as the dimensionless pressure, established the dimensionless gas flow equation around the borehole, and solved it by developing software on his own. Through dimensionless analysis, a new test method for coal seam permeability coefficient is established.

In "Statistics of coal and gas outburst accidents and numerical inversion of typical cases", Chaojun Fan, from Liaoning Technical University, presented coupling relations of damage-seepage in outburst coal seam and established the governing equations. A numerical inversion of typical case in Pingdingshan Coal Mine area was carried out. The evolutions of stress, gas, and energy in coal seams, as well as the scale range of outburst geological body, were obtained.

Wei Liu, from the China University of Mining and Technology (Beijing), delivered a presentation on "Theoretical model and experimental verification of free gas diffusion in coal particle micropores". A spherical coal matrix gas diffusion model driven by free gas density gradient was established and was proved by a new inversion method for diffusion coefficient. Then the advantages of the new diffusion model with traditional models were compared, providing new ideas for the mechanism of coal matrix gas flow.

Shoujian Peng, from Chongqing University, presented a talk entitled "Research on the physical simulation of coal-gas two-phase flow migration law and its dynamic disaster-causing characteristics under complex roadway conditions". A large-scale physical simulation test system of multi-field coupling dynamic disasters was established to carry out dynamic disas-

ter test of coal and gas outburst considering different gas pressures, in-situ stresses and roadway forms. The spatiotemporal evolution law and coupling mechanism of middling coal stress, gas pressure, temperature and other physical field parameters in the process of coal and gas outburst were revealed.

In the lecture of "Quantitative characterization and visualization of gas emission based on gas desorption infrared radiation", by Zhonghui Li, from the China University of Mining and Technology, the variation law of infrared radiation in the process of adsorption and desorption were introduced. Then influencing factors of infrared radiation in adsorption and desorption process of gas-bearing coal were analyzed. At last quantitative characterization and visualization of gas emission in gas emission process were obtained. Due to this study, the visual characterization of gas desorption is realized.

In "Propagation law of outburst two-phase flow and evolution mechanism of outburst energy", Chaolin Zhang, from the China University of Mining and Technology, studied propagation law of two-phase flow and proposed evolution mechanism of outburst energy. During outburst process, the roadway air is compressed to produce multiple shock waves. The outburst pulverized coal flow has the multiple reacceleration processes and the energy of outbursts generally comes from gas expansion energy.

In a presentation on "Analysis and understanding of the propagation law of fractures in coal under gas effect", given by Dengke Wang, from Henan Polytechnic University, he presented gas seepage model of loaded gas-bearing coal, based on the analysis for the influence of gas pressure on the fracture expansion of coal under non-loaded conditions and the influence of gas pressure on the fracture expansion of coal under loaded conditions. As he emphasized, fractal dimension can be used to describe the fracture propagation and damage degree of coal under compressive loads. Euler number could effectively reflect the evolution of fracture connectivity during the stress-strain process.

Zhongbei Li, from the University of Wollongong Australia, presented a talk entitled "Theoretical and experimental studies on sorption characteristics of different-composition gas and its hysteresis effect". He elucidated the underlying mechanisms of gas adsorption and desorption hysteresis, as well as the fundamental reason for the existence of residual gas. Building on this insight, an enhanced Langmuir-based desorption model was introduced, accounting for the observed phenomena. Through this model, the impact of gas composition and sorption hysteresis on coal and gas outburst was determined. Notably, under Australian current gas-content based outburst threshold limit values, CO_2-rich coal seams do not pose a higher outburst initiation energy risk compared to CH_4-rich coal seams.

Junqing Meng, from the China University of Mining and Technology (Beijing), presented a talk entitled "Influence law and failure mechanism of adsorbed gas on coal microcrystal structure". He established the gas adsorption model of coal and obtained that the adsorbed gas has a destructive effect on the microcrystalline structure of coal. Methane molecules absorbed heat to convert it into kinetic energy to maintain diffusion. Methane molecules were preferentially adsorbed on the aromatic structure and carried out Knudsen diffusion movement in the gap between aromatic lamellae and collided with aromatic lamellae.

Liming Qiu, from the University of Science and Technology Beijing, gave a presentation on "Wave velocity response mechanism and seismic wave CT detection index selection of coal seam outburst danger: experiment and case study". He revealed the wave velocity distribution before and after hydraulic fracturing, and the wave velocity distribution during coal roadway driving by experiments. As he emphasized, in order to better predict coal and gas outburst, seismic wave CT inversion detection technology can be used to confirm and analyze the wave velocity Vp, wave velocity anomaly coefficient An, and the gradient of wave velocity variation VG wave velocities to identify areas with significant changes in stress disturbances on site.

Xiangguo Kong, from the Xi'an University of Science & Technology, presented a talk entitled "Dynamic fracture of coal and gas migration laws under impact load". He established a gas releasing model under impact disturbance. Dynamic experiments of gas-bearing coal are carried out to obtain the dynamic mechanical properties of gas-bearing coal. The theoretical value of the established gas releasing model under impact disturbance is consistent with the experimental value. This gas releasing model can be used to predict the gas emission laws induced by impact disturbance in the stope environment.

In the talk on "Kinetics research on formation and decomposition of mine gas hydrate in coal based on impedance testing method", delivered by Qiang Zhang, from the Heilongjiang University of Science and Technology, proposed the use of hydrate method to prevent coal and gas outburst. Modeling of gas hydrate saturation calculation based on impedance technique was established. Hydrate-containing coal body gas dissolution and desorption pre-study experiments are carried out to obtain the decomposition process of gas hydrate in coal.

4. Mechanism, monitoring and prevention technology of mine fire

In 2022, the total production of raw coal in China was 4.56 billion tons, and coal account for 56.2% of primary energy consumption. Mine fire has caused serious economic, environmental and social problems. In this section, twelve researchers induced current progress for the fire disasters in coal mines and their prevention and control.

Jun Deng, from the Xi'an University of Science and Technology, delivered a talk entitled "Research and prospect of high temperature point identification and detection technology for coal spontaneous combustion in goaf". Based on the deduced relationship between the acoustic signal and temperature, he found that the acoustic temperature measurement method can realize the reconstruction of the temperature field, so as to determine the high temperature location of the goaf. Based on this discovery, he developed a monitoring system that can achieve remote, non-contact, and real-time temperature monitoring, effectively identifying and tracking potential fire sources.

In the lecture of "The explosion rules and macro-, meso- and micro-scopic mechanisms of coal dust explosion", by Baisheng Nie, from Chongqing University, he conducted coal dust explosion experiments on anthracite, lignite, and bituminous coal, analyzed the characteristic parameters of gas pressure and composition in each stage of coal dust explosion, and obtained the active bonds that are easy to break in the process of high temperature thermal excitation. The reaction paths and thermodynamic parameters of the main functional groups in the coal macromolecular structure are revealed.

Jian Zhang, from Henan Polytechnic University, delivered a presentation on "Distribution characteristic of heat regulating ring around coal mine roadway". He conducted measurements of the primary rock temperature, thermosphere, formation thermal property parameters, and numerically simulated heat-regulating rings in tunnel enclosures. He found that the main and secondary effects of each factor on roadway wall temperature are as follows: ventilation time $>$ airflow velocity $>$ primary rock temperature $>$ temperature conductivity $>$ airflow temperature $>$ airflow humidity.

Ke Gao, from Liaoning Technology University, presented a talk entitled "Numerical simulation of gas and two-phase explosion based on OpenFOAM". He used OpenFOAM to investigate the effect of a very low gas concentration in a return tunnel on the gas explosion characteristics in the underground tunnels of coal mines. Methane/coal particle/air mixtures were simulated using the Eulerian-Lagrangian method and a detailed chemical mechanism. A zero-dimensional constant-volume approach was employed to investigate the impact of particle diameter, particle concentration, and initial pressure on the two-phase ignition process.

In the talk on "Application of thickened slurry to prevent and control coal spontaneous combustion in overlaying goaf - A case study in Anyuan Coal Mine, China", delivered by Yi Lu and Xiaoying Wu, from the Hunan University of Science and Technology, they prepared a new type of thickened slurry for preventing coal spontaneous combustion in overlying goaf was prepared based on polymer material, surfactant, loess and water. Thickened slurry fire prevention and extinguishing technology to control the spontaneous combustion of coal in the overlying goaf had achieved good results.

Jinhu Li, from the Anhui University of Science and Technology, delivered a presentation on "Discovery of the key active substance leading to the room temperature oxidation of raw coal". He analyzed the redox process and found the primary active sites in coal and the active sites generated by thermal decomposition belong to the same free radical structure, which provides initial heat source for coal self-heating of coal. The discovery of active sites is helpful to reveal the mechanism of coal spontaneous combustion and points out the direction for exploring the internal causes of coal spontaneous combustion after gas drainage and CO overrun in low-rank coal mines.

In "Study on gas-liquid coaxial jet foam generator and its foaming characteristics", Caiyuan Lu, from the China University of Mining and Technology, carried out a comparative experiment to research the influence of liquid flow, gas flow rate, outlet diameter and foam generator to foaming performance. He found that the gas-liquid coaxial jet foam generating device has better advantages compared with similar devices in terms of foaming multiplier and range.

5. Other research topics

Tingxiang Ren, from the University of Wollongong Australia, delivered a talk on "Reducing respirable mine dust exposure in development panel-A Computational Fluid Dynamics (CFD)-Virtual reality (VR) based training tool for workforce". The hazard of coal mine dust in industry issues and mine dust lung diseases were discussed. He introduced that monitoring and computational modelling can help better understand dust/ventilation behavior in various cutting scenarios and make more informed decision/controls. He pointed out that CFD-VR based training tool can enhance WH&S awareness, health outcomes and productivity.

Wen Nie, from the Shandong University of Science and Technology, delivered a talk on "Study on temporal and spatial evolution law of dust in fully mechanized excavation face and efficient dust control technology". The report mainly carried out in four aspects: theoretical innovation, experimental research, technology development and equipment development. He proposed an accurate macro and meso dust prediction and analysis method, revealed the dust pollution mechanism in fully mechanized excavation face of low and high gas concentration, innovatively developed the full section dust control method of multi-radial swirling air-curtain, developed a key technology system of an efficiently wetting and coagulating enhancer for dust removal.

Sikandar Azam, from The Pennsylvania State University under Shimin Liu's supervision, delivered a presentation on "Numerical modeling of moisture transport behavior in the sub-micron-sized coal particulate: A transient approach". He analyzed changes in the density (specific gravity) of the individual coal dust particles, changes in the porosity of the individual coal dust particles and implications of wettability on flow behavior of nano-size coal particulate. The modeling results can be used for the dust-mine air interaction and ultimately provide guidance for the nano-sized dust control.

Deji Jing, from Liaoning Technical University, delivered a talk on "Design of De-Laval supersonic atomizing nozzle and study on spray characteristics". He designed a De-Laval supersonic atomization nozzle based on the supersonic atomization mechanism. Through comparative experimental analysis, he obtained that the particle size of the De-Laval supersonic atomizing nozzle was 38.89% smaller than that of the pressure nozzle at different distances, and 40.64%$\sim$52.32% smaller than that of the pressure nozzle at different pneumatic pressures, indicating that the droplet crushing and atomizing effect of the De-Laval supersonic atomizing nozzle was better.

Xiangjun Chen, from Henan Polytechnic University, delivered a presentation on "Study on air flow migration in goaf under the mining mode of roof-cutting and pressure-releasing". He introduced the evolution model of void ratio and permeability of goaf in roof-cutting and pressure-releasing mining based on numerical analysis and field measurement, revealed the law of air flow movement in the working face

and goaf, and proposed air leakage prevention and control technology.

Ding Cui, from the China University of Labor Relation, presented a talk entitled "Research on the air flow stability characteristics in turning mine tunnels". She reported that the distance that air flow retune to a symmetrical circular structure gradually increases as the ventilation velocity increasing. Ventilation velocity is a key factor affecting the stable distance of airflow in the turning tunnel. The relationship between the stable distance of airflow and the turning angle fit a good logarithm function. The relationship between stable distance of air flow and the ventilation velocity fit to a good exponential function.

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Conflict of interest

The authors declare no competing interest.

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