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Gas Drainage Borehole Technology and Intelligent Management Systems in Coal Mines: A Review

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Abstract: Gas extraction is one of the means to control gas disasters in coal mine production. Coal mine gas is not only a major disaster source, but also an important clean energy. Gas extraction drilling technology is the main technical means of underground coal mining. With the increase of mining depth, gas pressure, content and outburst risk increase significantly. Efficient extraction and accurate early warning have become the core issues to ensure mine safety and resource utilization. This paper systematically reviews the research progress of gas extraction drilling technology optimization, extraction effect evaluation method and intelligent early warning mechanism, and looks forward to the future development trend of new technologies.

Keywords: Coal mine gas; Gas drainage borehole; Early - warning mechanism; Intelligent management system.

1. Introduction

In coal mine production, coalbed methane (CBM) serves not only as a major source of safety hazards but also as a significant clean energy resource. With the annual increase in mining depth, the pressure, concentration, and sudden risk of coalbed methane have risen significantly, posing greater challenges to coal mine safety. Statistical data indicate that gas-related accidents account for over 70% of total coal mine disasters, underscoring the critical importance of gas management. To effectively mitigate gas hazards, the implementation of gas drainage has become an urgent necessity.

Gas drainage technologies in coal mines primarily involve the construction and management of drainage boreholes. The rational layout and construction techniques of these boreholes directly influence drainage efficiency. Depending on geological conditions and mining methods, drainage boreholes can be categorized into various types. In recent years, traditional rotary drilling technologies have gradually been replaced by advanced techniques such as near-horizontal directional drilling, branch hole construction, and large-diameter long-hole drilling. These innovations not only enhance drilling efficiency but also improve safety and operational flexibility.

However, the drilling process is susceptible to multiple factors, including borehole trajectory deviations and emission blind zones, which may compromise gas drainage effectiveness and threaten mine safety. Consequently, researchers have conducted extensive studies on borehole construction and management, proposing optimization strategies and technical solutions to improve drainage efficiency and safety.

Furthermore, the integration of intelligent management systems, driven by advancements in information technology, offers new approaches to gas drainage management. Leveraging next-generation technologies such as the Internet of Things (IoT), big data, and cloud computing, real-time monitoring and management of gas emission boreholes can be achieved, enabling timely identification of potential hazards and strengthening mine safety.

In summary, research on coal mine gas drainage technologies and intelligent management systems holds significant theoretical importance while providing practical technical support for industrial applications. Future developments should focus on further optimizing gas drainage techniques, refining early warning mechanisms, and advancing the implementation of intelligent management systems, all of which remain critical challenges in the field of coal mine safety production.

2. Construction of Drainage Boreholes and Early - warning Mechanism for Drainage Effects

Gas accident disasters rank first among coal mine production hazards in China, severely impacting mine safety[1]. With the continuous increase in mining depth and intensity, gas emissions from working faces continue to rise. Abnormal gas emissions causing gas concentration exceedances in working faces have become a major safety hazard during mine production. Currently, the most widely used technology is gas drainage borehole technology. Based on borehole strata positions and drainage purposes, underground gas drainage boreholes can be categorized as in-seam boreholes, cross-seam boreholes, and high-level boreholes. Using various hole-forming techniques and drilling rigs to construct different types of boreholes has formed diverse underground gas drainage borehole construction technologies[2]. The layout of boreholes should be reasonably determined according to coal seam occurrence conditions and roadway excavation directions[3].

For a long time, the traditional rotary drilling technology has been the main method for underground borehole construction in coal mines. In the past decade, new technologies such as near - horizontal directional drilling, branch-hole construction, large-diameter long - borehole construction, turning borehole construction, air drilling, and the use of triangular drill pipes and spiral drill pipes for drilling in soft coal seams have been successfully developed. The supporting construction equipment has evolved from ordinary single - split drilling rigs to walking and crawler -

type rigs with high drilling efficiency, strong process adaptability, safe operation, good disassembly performance, and easy relocation. The types and specifications of supporting drill pipes and drill bits are diverse, continuously meeting the requirements of coal - mine gas drainage borehole construction.

In particular, the innovation and development of near - horizontal directional drilling technology have revolutionized underground mine tunneling technology in coal mines, filling the domestic gap and providing a new solution for underground gas control in coal mines. Directional drilling technology features high drilling efficiency, high accuracy in borehole trajectory control, and strong construction operability. Other equipment has also become serialized to meet the construction requirements of different roadway conditions. After the application of directional drilling technology, the number of gas drainage boreholes in working faces has been reduced, and long - borehole gas drainage has been achieved[4]. Moreover, an effective application of directional drilling technology in comb - shaped borehole construction has been formed, addressing the problems of poor borehole formation, short drainage distance, and small drainage area in soft coal seams, and realizing long - distance and regional gas drainage in soft coal seams, which has made important contributions to the development of coal - mine gas control technology.

2.1. Construction of Drainage Boreholes

However, the borehole construction process is affected by multiple factors and will encounter various problems. For example, Si Fei[5]proposed a construction technology for directional long - borehole gas drainage in working faces to solve the problem of gas drainage blank zones in bedding borehole construction during coal - seam gas drainage in working faces; Du Jun[6], Sun Rongjun[7] et al. proposed a coal - and - gas co - mining system combining pre - drainage boreholes and high - level boreholes to address the problems of high construction cost and low operation efficiency in the special roadway and buried - pipe methods for goaf gas utilization; Pi Xiyu[8]et al. developed a lightweight, compact, and low - cost guiding and dust - capturing integrated device to suppress the dust diffusion speed during dry drilling in coal - roadway gas drainage borehole construction, reduce the dust concentration at the operation point, and ensure the health of operators and mine safety; Wang Qing[9], Zhang Zairong[10], Hao Dian[11]et al. proposed a directional drilling technology for underground pressure - relieved gas drainage in coal mines, developed a borehole - mouth anti - spray device, and constructed a refined management model for borehole construction and gas drainage with the requirements of “drill to the target, pipe to the end, seal the borehole tightly, drain the water smoothly, ensure sufficient negative pressure, conduct frequent inspections, keep the site clean, and have complete data, and prevent over - limit spray holes”; Liu Xuetong[12], Lou Yahui[13]et al. used theoretical analysis and numerical simulation methods to study the deflection control technology, deflection law, and engineering application of gas drainage boreholes to solve the problem that the borehole trajectory seriously deviates from the design trajectory during gas drainage borehole construction, which easily leads to gas drainage blind zones and safety hazards; Lin Haifei[14]established a fluid - solid coupling drainage model for gas - containing coal, analyzed the influence law of the interaction between geological factors and engineering factors on pre - drainage of coal - seam gas by boreholes using the COMSOL Multiphysics simulation software, proposed a borehole layout parameter determination index of the ratio of the maximum gas pressure between boreholes to the standard - reaching pressure (P_{max}/P_b), innovated a precise borehole layout method for pre - drainage of coal - seam gas by bedding boreholes, obtained the optimal borehole layout parameters suitable for different coal - seam gas occurrence characteristics, and conducted on - site tests; Zhao Hongxing [15] proposed a gas drainage method combining high - and low - level boreholes and large - diameter long - boreholes along the roof strike to address the problem of large gas emission from the upper adjacent coal seams during the initial mining and normal mining periods; Shen Zhongsheng[16] et al. developed a stability maintenance device for gas drainage boreholes to maintain the stability of gas drainage boreholes with different diameters.

2.2. Early - warning Mechanism for Drainage Effects

Many scholars have conducted extensive research on the early - warning mechanism for drainage effects. For example, the common early - warning method is to conduct daily gas early - warning through the abnormal monitoring indicators of the monitoring system[17]; Liu Yanhong[18] analyzed the reliability of the early - warning system; Cheng Hao[19] proposed an evaluation index system for goaf gas drainage effects and constructed a gas drainage effect evaluation method based on the game theory - cloud model through methods such as engineering data collection, theoretical analysis, evaluation model construction, and on - site engineering application; He Shun[20] constructed a coal - seam gas parameter inversion model to address the problem that the current conventional index prediction method in coal mines is difficult to achieve real - time and continuous prediction of outburst danger, continuously revised the model inversion parameters according to the geological parameters and tunneling procedures of the test mine, and verified the inversion model; Li Haichen[21] developed a new wireless gas sensor network system; Wu Xingyun[22] designed a B/S - architecture statistical software by constructing a local - area network data - sharing hardware platform to realize rapid query and statistics of data, chart display, and interconnection and sharing; Xie Xu [23] realized the collection of parameters such as CH_4 concentration, C_2H_4 concentration, CO concentration, flow rate, negative pressure, and temperature in the drainage pipeline based on PLC intelligent control technology, established its logical control set, and controlled the operating states of underground explosion - proof drainage pumps and main - pipeline negative - pressure control valves; Han Chao[24] designed an intelligent cloud - platform model for the mine gas drainage system based on technologies such as the Internet of Things, 5G communication, cloud platform, and big - data analysis.

3. Development of Intelligent Management System for Gas Drainage Boreholes

The new - generation information technologies such as the Internet of Things, big data, cloud computing, industrial Internet, 5G, and artificial intelligence are booming and widely penetrating into traditional fields, triggering a group - based technological revolution characterized by intelligence, which is promoting the transformation and upgrading of traditional industries[25]. In the current intelligent era, coal - mine intelligence represents the development direction of advanced productive forces in the coal industry, helps to quickly solve the contradictions and problems in the coal industry, promotes the transformation and upgrading of the coal industry, and is the core technological support for the high - quality development of the coal industry[26].

Many scholars have studied the development of intelligent management systems for gas drainage boreholes. Huang Jingjing [27] designed an intelligent information management system for gas drainage boreholes, established an exponential smoothing model for borehole gas flow within a cycle based on the time - series prediction method, and set up a three - level management mechanism for borehole control valves in combination with the actual situation; Guo Heng et al. [28] proposed a refined control mode for gas drainage boreholes based on data - driven; Wang Dianqing[29] et al. analyzed the functions of the underground gas drainage borehole management and analysis system developed by Changping Mine according to its own underground coal - seam gas drainage status, including borehole trajectory measurement, intelligent design of drainage boreholes, borehole information management, auxiliary analysis of measure defects, and analysis of borehole control effects; Chen Rui[30] designed and developed a bedding drainage borehole review system to address the problems of low efficiency and poor accuracy in the bedding borehole layout review work under complex geological conditions; Dai Chenyu[31] proposed to construct a borehole gas drainage monitoring system with boreholes as monitoring units to dynamically and real - time grasp the drainage effect of each borehole, realizing refined monitoring of gas drainage. The Gas Drainage Borehole Trajectory Intelligent Monitoring System independently developed by the New Materials R & D Project Department of Shaanxi Coal Industry Group's Research Institute uses the principle of military inertial navigation technology to solve the problems of collecting, storing, and managing the inclination, azimuth, face angle, and drilling depth of various boreholes under complex coal - mine conditions. The Coal - Mine Gas Drilling Site Video Intelligent Analysis System uses artificial - intelligence machine - vision technology to real - time identify the drilling depth, drilling time, and drilling angle. It operates without perception throughout the process, reducing human intervention, and achieving staff reduction and efficiency improvement. It also realizes functions such as mobile - terminal access and approval, allowing users to access the system via mobile phones at any time and anywhere to real - time grasp the coal - mine gas drainage operation situation and implement gas control measures.

The underground working environment of coal mine is complex, and the hidden danger of disaster is prominent. The traditional extraction drilling technology causes the construction personnel to face higher safety risks. In view of this situation, the research and development of intelligent drilling equipment with independent operation ability, and the construction of drilling operation system based on intelligent perception and remote monitoring have become an important technical path to ensure mine safety production. By promoting the deep integration of drilling technology and intelligent equipment, the unmanned, remote control and automatic intelligent construction of underground drilling operation can be realized, which can not only significantly improve the operation safety in high-risk environment, but also has important engineering practice value for promoting the intelligent transformation and upgrading of coal industry.

4. Conclusions and Perspectives

Based on the comprehensive review of gas drainage borehole technology and intelligent management systems in coal mines, several key conclusions and future perspectives can be drawn:

4.1. Conclusions

Advancements in Drilling Technologies: The development of directional and comb-shaped drilling technologies has significantly addressed the challenges posed by soft coal seams. These innovations have improved drilling efficiency and effectiveness in gas drainage, thereby enhancing safety in coal mining operations.

Integration of Intelligent Systems: The application of Internet of Things (IoT) and artificial intelligence (AI) has facilitated real-time monitoring and management of gas drainage boreholes. These intelligent systems enable timely responses to gas emissions, improving overall mine safety and operational efficiency.

Robotic and Automated Solutions: The emergence of robotic prototypes and automated drilling equipment represents a substantial step towards unmanned operations in hazardous underground environments. This advancement not only reduces the risk to human operators but also enhances the precision and reliability of drilling activities.

4.2. Perspectives

Standardization and Scalability: Future research should focus on establishing standardized early warning thresholds and enhancing the scalability of intelligent systems across various mining operations. This will ensure that advancements can be widely adopted and effectively implemented in different geological contexts.

Cross-disciplinary Integration: There is a pressing need for cross-disciplinary collaboration, particularly between geomechanics and AI, to develop more robust predictive models and management systems. Such integration can lead to innovative solutions that address the complex challenges of gas drainage in coal mines.

Cost Reduction Strategies: To promote the industrial adoption of intelligent technologies, efforts should be directed towards reducing costs associated with the implementation of advanced monitoring and drilling systems. This will facilitate broader access to cutting-edge technologies, ultimately contributing to safer and more efficient coal mining practices.

In conclusion, the continuous evolution of gas drainage technologies and intelligent management systems holds great promise for enhancing safety and efficiency in coal mining. By addressing existing gaps and fostering innovation, the coal industry can achieve sustainable development aligned with the core socialist values of safety, responsibility, and environmental stewardship.

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