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Research article

Unveiling the Catastrophic Mechanism of Coal and Gas Outbursts: Strategies for Prevention and Control

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Abstract

In the realm of deep coal mining, a notable difficulty faced is the occurrence of methane gas and abrupt emissions of coal gas. This study scrutinizes coal gas outbursts via laboratory investigations. The study investigates the dynamics of coal gas outbursts, focusing on the analysis and mitigation of abrupt coal gas releases via laboratory experiments. Results suggest that the prevention of coal gas outbursts in the test sample is achievable by a 20% pressure reduction using degassing techniques.

Drawing from engineering observations during the mining process, this study investigates the mechanism of coal gas outbursts using a specifically constructed test device. This study reveals that a gas outburst occurs when the boundaries of coal seams become unstable due to coal failure. In cases where fractures are not connected or are closed due to coal/rock stress, the fractured zones can maintain a certain level of carrying capacity due to self-sealing gas pressure. However, once the accumulated gas energy reaches a critical point, the coal seams become unstable, leading to gas outbursts. This study presents a laboratory analysis of coal gas outbursts, methane drainage, and methods for managing these events. Findings indicate that the outburst of coal gas can be effectively managed by lowering the tank pressure through gas drainage techniques.

1. INTRODUCTION

A coal and gas outburst, recognized as a severe hazard in coal mining, involves the sudden expulsion of large quantities of fractured coal and gas from a coal seam into the mining area.

During a sudden outburst of rock and gas, a boundary surface develops, dividing the undisturbed rock region from the area filled with crushed rock and gas. This surface progresses into the undisturbed rock body as the crushed material and gas are displaced into the mine workings (Litwiniszyn, 1986). Sudden outbursts in underground coal mines have been documented in over countries, involving both methane (CH_4) and carbon dioxide (CO_2). The specific mechanisms behind these sudden outbursts are still not fully understood but must take into account the influence of stress, gas content, and the physico-mechanical properties of the coal. Additionally, mining methods (such as development heading into the coal seam) and geological features (such as coal seam disruptions from faulting) can contribute to exacerbating the issue. Prediction techniques remain unreliable and unexpected outburst incidents resulting in fatalities are a significant concern for underground coal operations(Beamish & Crosdale, 1998).

Various elements that impact this occurrence, such as geological circumstances, coal's physical characteristics, the amount of gas, and the gas pressure, are examined (Lama & Bodziony, 1998). Research into the impact of water absorption and/or methane adsorption on coal fracture parameters allows for the forecasting of outburst conditions in certain coal layers, and their prevention hinges on the discovery that water content exceeding approximately 3% renders the outburst-type fracture mode unfeasible (Alexeev, Revva, Alyshev, & Zhitlyonok, 2004). A set of gas measurement tubes was engineered to record gas pressure, its fluctuations, and the effects of adjacent operations to identify areas susceptible to outbursts. The effectiveness of injection as a mitigation technique was demonstrated using these tubes. While injection lowers gas pressure within the coal seam, the test should be carried out with the utmost precautions, as gas outbursts could happen during the procedure (Aguado & Nicieza, 2007).

From a mechanical perspective, a coal and gas outburst represents a form of coal failure. The failure modes of coal specimens are typically categorized as shear yielding or tensile fracture. Test results are commonly analyzed by constructing an envelope equation of their Mohr's circle, which combines circles representing failures due to tension, compression, and shear to establish the strength conditions (Hongwei, Qianting, & Yanbao, 2011). The phenomenon of slip cracks in coal specimens in a one-dimensional shock tube test is indicative of failure due to tension. Tri-axial compression tests demonstrate the yield phenomenon due to shear. While shear yielding alone may not directly cause gas or coal outbursts, it could occur prior to tension fractures. Therefore, stress-strain relations of coal after shear yielding should be determined through dynamic calculations. This can lead to the establishment of rules governing regular and associated flows, based on shear yield experiments that determine relevant parameters (Huang, Zhanqing, Jianhua, Zhang, & Min, 2010).

Coal bed methane content in the heading faced oesnot decrease by the effect of the degasification boreholes orby the influence of the road way driven with the short wall sublevel caving method (Torano, Torno, Alvarez, & Riesgo, 2012). The development of outburst shockwaves and gas movement has been studied, and numerical simulation models for roadways intersecting at 45 and 135 degrees have been created to mimic the spread of outburst gas flow and the gas transportation process. It was found that as the angle between the excavation roadway and the nearby roadway grew, there was a greater range of sudden pressure fluctuations in the adjacent roadway and an expanded area affected by the gas flow, while the duration of such pressure changes shortened. However, the point of intersection between the excavation and adjacent roadways does not influence the reversal of airflow caused by the shock waves and gas flow (A. Zhou, Wang, & Wu, 2014). The dynamic system outburst comprises three fundamental components: the coal-gas medium (the material foundation), the geological dynamic environment (the internal driver), and mining disturbances (the external driver) (Fan, Li, Luo, Du, & Yang, 2017). In 2018, Yang and associates conducted laboratory research on the early gas release and behavior of coal gas outbursts. Selecting seven coal samples representing various metamorphic stages, they performed outburst simulation experiments to investigate the gas release trends from pulverized coal when subjected to N2 and CO2 exposure. The results indicated a marked correlation between the rates of gas emission in the initial 10 seconds and the inherent desorption of natural gas from the coal during the initial 120 minutes following exposure (Yang et al., 2018). Cao, Dai, and their team investigated the influence of adsorption characteristics on coal and gas outburst phenomena by performing simulation experiments in CO2 and air, utilizing a custom experimental system to analyze both the gas pressure and the dispersion of coal dust released during outbursts. They employed energy theory to elucidate how the properties of adsorption affect the dynamics of the outbursts (Cao et al., 2019). Pan and associates developed a specialized testing apparatus to examine the mechanisms behind coal and gas outbursts in tectonically active zones. They conducted controlled laboratory outburst experiments using unprocessed coal samples taken from an outburst-prone coal seam in a Chongqing mine situated in a tectonic area. The experiments on these tectonic coal samples were conducted under different gas pressures and stress conditions (Pan, Cheng, Chen, & Zhou, 2020). In 2022, Zeng and colleagues created an advanced setup that included a chamber for coal samples, a loading mechanism, a gas release system, real-time data collection capabilities, and several supplementary components. Employing this equipment, they performed immediate gas emission tests on stressed coal samples interacting with different gases. These experiments focused on analyzing coal sample breakdown, fluctuations in gas pressure, shifts in axial stress, and the evaluation of potential outburst hazards (Zheng, Huang, Cheng, Jia, & Cai, 2022). During the LSTT experiments, it was noted that coal and gas outbursts resulted from the interplay of stress and gas pressure in a restricted zone of equilibrium. The stress induced by mining operations emerged as a critical factor in the occurrence of coal and gas outbursts (Shang et al., 2023). In their 2023 research, Wang and Cheng investigated how the energy from coal deformation affects the incidence of swift gas discharges. Their study systematically reviewed research techniques and current debates in the field of energy related to coal and gas outbursts. Emphasis was given to Hodot's energy criterion, which prioritizes coal deformation energy. They outlined methods for characterizing and roughly quantifying both coal deformation energy and the energy from gas expansion. Furthermore, they scrutinized the release processes and the comparative importance of coal deformation energy versus gas expansion energy in triggering outburst incidents (Wang & Cheng, 2023). In their 2023 investigation, Zhang and colleagues delineated a four-phase sequence in the dynamics of coal and gas outbursts: the preparatory phase, the triggering phase, the expansion phase, and the termination phase. They recognized that the actual outburst transpires during the expansion phase. The experimental setup included 77.531 kilograms of coal and 3.593 kilograms of yellow mud compaction, which ultimately led to 20.125 kilograms of coal being expelled. The aperture of the outburst was shaped like an ellipsoid, featuring a constricted entrance and an expansive internal cavity. The study corroborated this four-stage model and observed intricate seismic signals with a broad range of frequencies that escalated to higher levels at the outburst climax. At the pinnacle of the event, these microseismic signals exhibited higher frequencies, although not the maximum energy. Sudden increases in amplitude during the preparatory and expansion stages suggested a higher likelihood of outburst incidents, with the peak moment energy matching up to frequencies as high as 45,000 Hz (Zhang, Zhou, Yang, Li, & Li, 2023).

Although numerous elements play a role in causing outbursts, pinpointing the most essential factors is difficult. Nonetheless, the pressure (or volume) of the gas and the permeability of the coal layer surface as primary factors. At elevated pressures, the reduced permeability of the coal seam results in intensified gas emissions as pressure rapidly propels the gas toward the mining face.

The article delves into the dynamic mechanism of coal mine outbursts and explores methane drainage methods using an innovative device, leading to laboratory investigations of the phenomenon.

2. SYSTEM DYNAMICS WITH VARIABLE BOUNDARIES (SDVB)

Two factors contribute to changes in coal seam boundaries: excavation and coal seam failure. Excavation-induced boundary changes are primarily linked to mining techniques, while failures occur unexpectedly before mining. These boundary shifts are the primary cause of complexity in coal seam movements. Coal seams interact with their surrounding rock and are influenced by gravity, gas pressure, and external disturbances. Failures in one area can reduce the coal-bearing capacity, leading to subsequent failures nearby. Consequently, the failure process of coal seam movement is characterized by evolving boundaries over time.

Due to the influence of gas pressure, gravity, and mining-induced disturbances, material in certain areas is disrupted, leading to the emergence and growth of fissures. These fissures weaken the load-bearing capacity of coal beds, and in turn, the failure zones in coal beds and their boundaries become variable. A significant characteristic of these changing boundaries is the continuous variation of interfaces between the failed and non-failed zones over time. The failed zones encompass the plastic zone, fractured zone, and over-broken zone as depicted in Fig. 1(Huang et al., 2010).

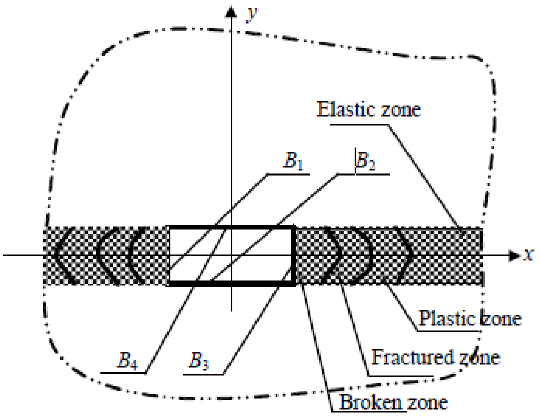

Fig. 1. Boundary between the elastic, plastic, fractured, and broken regions of a coal seam(Huang et al., 2010).

The stress distribution within coal seams is highly complex, involving shear yielding and tensional fractures. The transition between shear yielding and tensional fractures can occur, leading to a loss of tensile strength. Fractures in coal seams are rare and isolated points cannot cause them. Deformation maintains continuity with interfaces between different zones such as elastic, plastic, fractured, and over-broken. These interfaces continually change, resulting in a decrease in bearing capacity and the expansion of failed zones within coal seams.

2.1 Mechanism Of Coal And Gas Outbursts

The occurrence of gas outbursts depends on the development of fissures and changes in gas pressure. If the gas moves smoothly before the fractures and fissures connect, gas pressure will not continuously increase, preventing the accumulation of significant energy in coal seams and thus avoiding gas outbursts. However, if the fractures and fissures near the coal wall do not connect, gas migration will be restricted, causing stress to increase far away from the coal walls. This can push the gas to nearby fissures, leading to an increase in gas pressure around the fissures and the instantaneous connection of the fissures. This can result in the ejection of large amounts of coal powder into the working face and roadway, causing a coal and gas outburst. As gas pressure increases in the fissures, the gas coverage near the fissures expands, and with the discharge of gas into the fissures, the adsorbed gas near the fissures is converted into free gas, leading to a significant intensification of diffusion and seepage flows.

In reality, the “outburst front” serves as a type of variable boundary, and gas outbursts are categorized into six phases. The first phase involves the intact stress of the coal seam. In the second phase, stress concentrations occur, also known as the stress concentration or abutment pressure phase. The third phase, referred to as coal crushed by rock stress, entails the failure of coal seams under crustal stress. The fourth phase, coal split by gas pressure, sees coal bodies being torn apart by gas. In the fifth phase, the expulsion of coal and gas occurs due to the loss of spherical shell stability, leading to the instability of crustose zones in coal seams and the ejection of coal in these zones. Finally, in the sixth phase, there is the movement of coal and gas desorption, where gas desorbs from farther afield within the coal seams.

We can explain the process of outbursts from the perspective of SDVB. Prior to mining, coal seams are in a state of static equilibrium. When mining occurs, some material suddenly separates from the coal seams, releasing stress on new boundaries. According to the principle of effective stress, stress tensors near the new boundaries exhibit a tensional stress component. This tensional stress component makes brittle material prone to failure. Initially, fractures are generated near these new boundaries, termed “first-generation fractures.” Subsequently, due to the loss of bearing capacity near these first-generation fractures, “second-generation fractures” emerge near them. This pattern continues, leading to the emergence of third, fourth, and nth-generation fractures in a series. In reality, the generation and development of fractures are continuous processes, albeit described as discrete events for convenience.

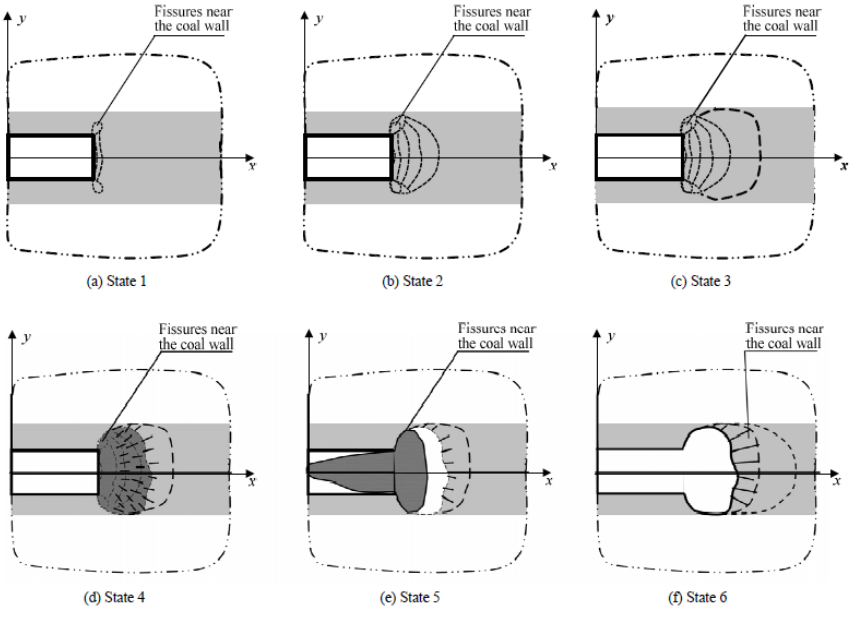

Fig. 2. Changes in boundaries occur over time during coal and gas outbursts(Huang et al., 2010).

One may inquire if there is a significant increase in the number of cracks spreading across the whole coal layer. However, this is not the case. This phenomenon can be attributed to coal or rock stress, analogous to the way the pressure and hardness of a bicycle’s outer tire influence the inner tube. The interaction of gas pressure and surrounding rock pressure can cause the coal seams to seal themselves, impeding the pathways for gas transmission. Close to the initial fractures, coal is less prone to breaking under tri-axial compressive forces as shown in Fig. 2c. Increased stress in the Earth's crust restricts gas pressure, potentially sealing cracks and impeding gas movement. This can lead to a rapid buildup of gas pressure and, if released suddenly, could result in significant damage. Without effective self-sealing, gas escapes through pores and cracks to the mined-out area, preventing pressure buildup as coal fragments, propelled by inertia and gravity, detach from the source. Dust and debris from the debris zone can further clog gas migration pathways. Over time, gas pressure gradually builds up until a displacement of these particles suddenly removes the blockage, leading to a sharp increase in gas pressure and potentially a violent gas emission. After such an event, the fissured areas not dislodged from the coal matrix might collapse or form stable load-bearing structures. Regardless of their state, the fissures' distribution, size, and orientation continually evolve. Fig. 2 illustrates the temporal boundary changes during gas and coal ejections. Fig. 2d illustrates the energy buildup pre-ejection, 2e depicts an intermediate phase, and 2f presents the state immediately following an eruption, setting the stage for subsequent incidents.

3. TYPES OF METHANE DRAINAGE

Methane gas in coal mines poses one of the greatest risks to mining safety. However, the advent of modern methane drainage fans can transform this hazard into a significant opportunity. Utilizing these fans not only heightens safety levels at mining sites but also allows for the harvested gas to serve as an energy source for the mine's operations or to take advantage of incentives offered by eco-conscious entities. Typically, methane extraction in coal mines is conducted via two primary methods: pre-mining drainage and post-mining drainage. Variations in geological formations and diverse mining practices across the globe have necessitated the adoption of assorted techniques for methane gas drainage. These techniques fall into three categories: pre-mining methanation, repeated pre-mining methanation, and judicious pre-mining methanation. Each method carries its unique set of pros and cons. When planning a methane extraction initiative, a thorough assessment of all relevant factors, alongside a technical and economic analysis, is essential. This process determines whether a solitary method or a combination of these approaches is most suitable. Depending on the depth of the coal seam and the quality of gas needed, the demethanization technique may involve vertical boreholes, horizontal boreholes, boreholes in the fracture zone, or intersection boreholes.

Fig. 3 presents an illustration of boreholes associated with the drainage process in a coal mine.

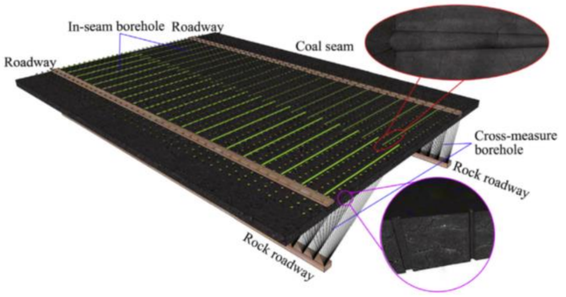

Fig. 3. Illustrative diagram of cross-measure and in-seam borehole placements.

In the collapsed area behind the longwall face, often referred to as the gob, methane gas tends to move toward the end of the return airway, leading to potentially hazardous levels that surpass regulated safety thresholds. To manage this, a drainage conduit is placed within the gob—a gob-embedded pipe to funnel the emissions toward the high corner, as depicted in Fig. 4. The terminus of this pipe is situated near the starting point of the face and is lengthened in tandem with the retreat of the mining face. When draining methane, a significant amount of air may enter the pipe; this design feature ensures that the return airway's atmosphere is drawn into the space within the gob, which helps to keep the methane concentrations from rising above the legally established safety limits (H. Zhou, Yang, Cheng, Ge, & Chen, 2014).

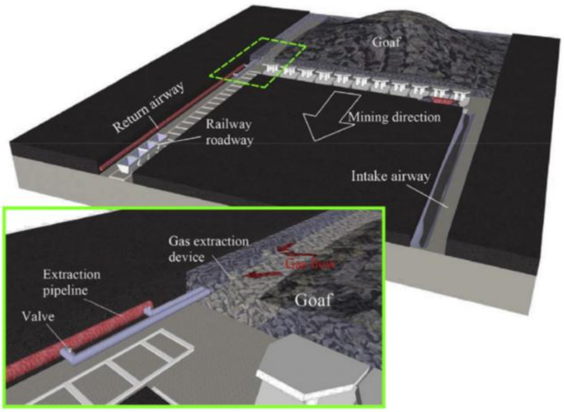

Fig. 4. Diagram of the goaf-embedded pipe technique.

4. LABORATORY STUDY OF OUTBURST AND METHANE GAS DRAINAGE

To conduct the test using the novel device for instantaneous coal gas outburst and gas drainage, a coal sample was duly processed and readied. Fig. 5 illustrates the innovative apparatus designed for examining coal outbursts and methane gas drainage.

Fig. 5. A new device for investigating the phenomenon of instantaneous emission of coal gas and drainage of methane gas.

Fig. 5 depicts the components of the device designed for simulating coal bed methane drainage and outbursts. The system includes a structural frame, a test chamber cylinder, a hydraulic cylinder, a vacuum pump, a gas storage unit, pressure sensors, solenoid valve-connected piping, a pneumatic valve, an electrical control panel with accessories, and a PLC with an HMI interface. The cylinder is constructed in accordance with the ASME code, a crucial standard for pressure vessels, and has dimensions of one meter in length, an inner diameter of 500 mm, and a wall thickness of 20 mm. Upon the assembly of the cylinder, including its sealing system, various electrical components and sensors were installed. These components included pressure and gas sensors, vacuum pumps with their respective sensors, and switchboard apparatus. Simultaneously, after setting up the system for immediate gas discharge, coal was placed in both the device and the cylinder. Following the requirements of the ASME standard, dual LUGs were designed and constructed to reinforce the support structure of the cylinder tank and were attached to the system. The device, designed to withstand a design gas pressure of 80 bars and operating temperatures ranging from 10 to 55 degrees Celsius, maintains stability with an ensured safety factor of 5.

The study focused on examining outburst and degassing by analyzing the impact of gas injection pressure in the double layers K10 and K21 of the Tazare mine. The details and qualities of this coal seam are outlined in Table 1.

Table 1. Properties of experimental coal samples

Type	Ash(%)	Moi(%)	VM(%)	S(%)
K10	55	2	23	9
K21	45	2	23	9

After the coal sample was set up and the procedure to assess coal gas outbursts was completed, the results were cataloged by the equipment. The pressure-time relationship in this study is depicted in Fig. 6. Referring to Fig. 6, 'P1' denotes the pressure in the tank and 'P2' represents the pressure at the outburst valve. A vacuum-formed inside the testing enclosure after the first 500 seconds, followed by the introduction of gas. The outburst in this test took place at a pressure of 3 bar, post which, upon activating the instantaneous gas release valve, the pressure indicator 'P1' dropped to zero within 5 seconds, after which the experimental cycle was initiated once more. The diagram of temperature over time is presented in Fig. 7. Following Fig. 7, the temperature during the test varied from 39.2 to 44.6 degrees. With time, due to reactions within the tank, there was a rise in temperature. In this specific trial, as the outburst occurred at a 3 bar pressure, the system's temperature logged was 40 degrees.

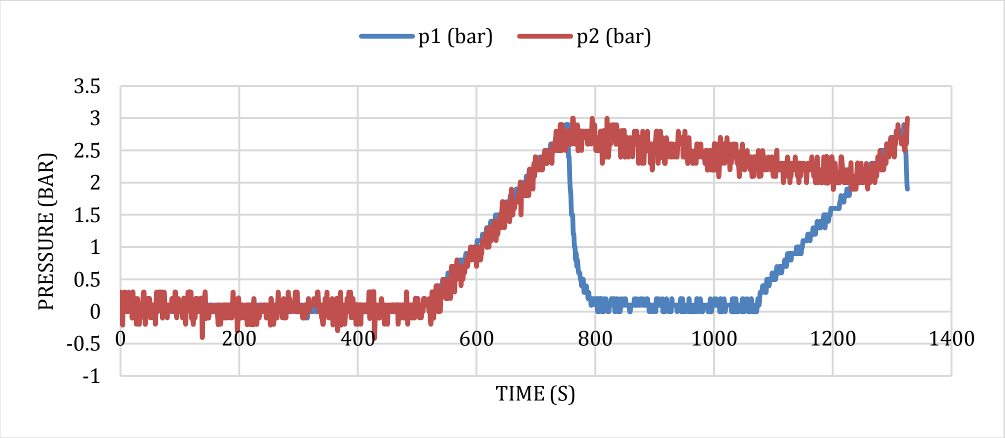

Fig. 6. Graph depicting the variations in pressure over time during the expansion of coal gas outbursts.

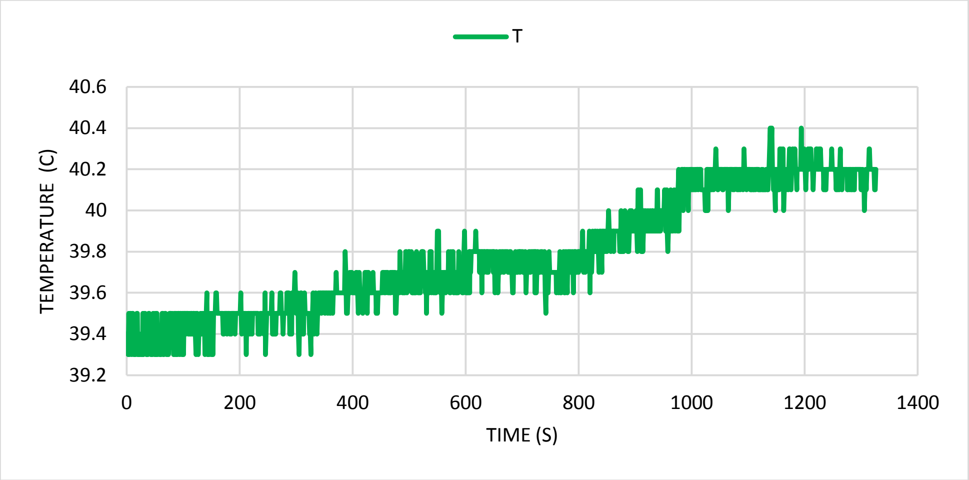

Fig. 7. Graph illustrating the temperature fluctuations over time in the expansion process of outburst coal gas.

To examine the effects of methane gas drainage on the occurrence of sudden coal gas emissions, a subsequent experiment was conducted using the same coal variety. The procedure is such that the Athens coal gas release valve was set to 3.5 bar, while the tank pressure and ground stress were maintained at 3.7 bar. The experiment was designed to trigger the suction pump to deflate the tank by 0.7 bar at ten-second intervals once it reached its peak pressure. As illustrated in Fig. 8, once the tank pressure hit 3.7 bar, the suction pump promptly lowered the tank's pressure to 3.2 bar, which did not result in any immediate coal gas emissions. Following this phase and a pressure decrease, a second non-draining test run was conducted. On this occasion, an instantaneous emission of coal gas was triggered at a pressure of 3.5 bar. It can be inferred that a 20% drop in pressure does not lead to a sudden release of coal gas in this coal type. Fig. 9 presents a graph of temperature changes over time throughout the methane gas drainage trial. As indicated by Fig. 9, the temperature fluctuated between 39.8 and 41 degrees Celsius during the test.

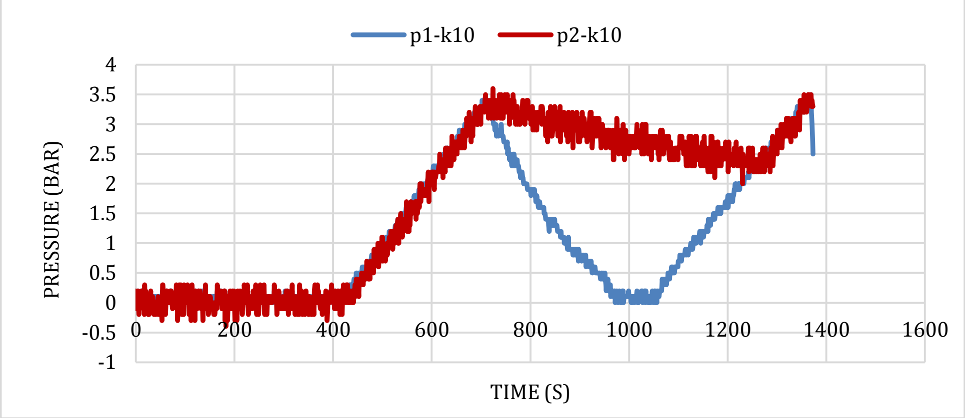

Fig. 8. Diagram depicting pressure over time during coal gas outburst and gas drainage experiment.

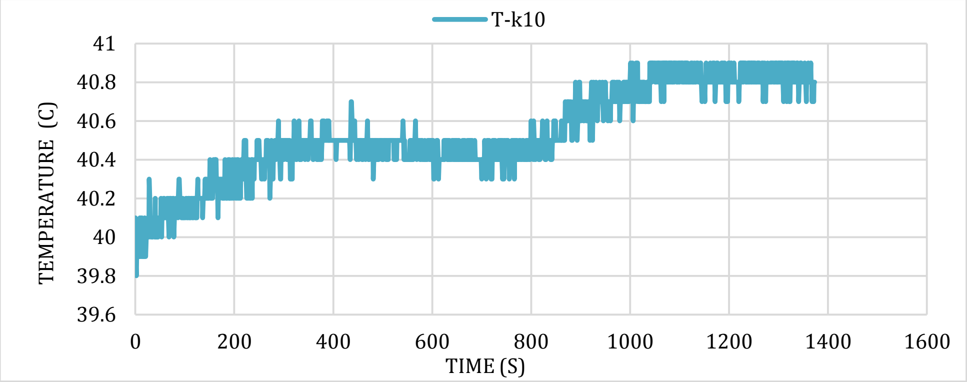

Fig. 9. Graph displaying the variation of temperature over time in a gas emission experiment.

The rise in temperature leads to an escalation in molecular motion, causing more frequent collisions with the container wall, resulting in an elevation of gas pressure within the container.

By constructing the new device based on scaling laws and analyzing different parameters to comprehend the phenomenon's behavior, the experimental results can be extrapolated to the actual conditions present in the mine.

The design of this device is based on dimensional analysis and scale change using P. Buckingham's theorem. Dimensional analysis involves analyzing problems using dimensionless parameters and variables instead of individual variables. By obtaining dimensionless numbers and using compression methods, dimensional analysis helps solve complexity and reduce the number of variables in a physical phenomenon. The main aim is to minimize variables and group them in a dimensionless manner. In the Pi-Buckingham method, functions are defined based on dimensionless independent parameters (Pi expressions) that include dependent physical parameters and are fewer than the variables in the original system. This approach allows for scaling relationships to be applied to different experiments and real mining conditions, enabling generalization from laboratory settings to mining operations.

5. CONCLUSION

The procurement of coal resources is predominantly executed using subterranean mining techniques, necessitating stringent adherence to engineering and technical rigor alongside established safety protocols and essential criteria. Currently, the majority of extraction activities transpire within gaseous regions of coal mines. Future expansions and the ongoing deepening of these mines will undoubtedly escalate the challenges posed by gaseous emissions. Concurrently, there should be a concerted push to adopt information technology by leveraging modern technological advancements and other resources to mitigate these risks effectively.

As the demand for coal necessitates deeper mining operations in the future, the phenomena and complications associated with this increased depth will also intensify in the pursuit of maximizing coal extraction. One particular issue inherent to the deeper excavation of coal seams is the heightened presence of methane gas, which escalates as mining activities reach further below the surface. In coal mines worldwide, one constant threat that remains undiminished and in fact, is on the rise, particularly in developing nations is the risk of explosions from gas and coal dust.Three core motivations underpin the extraction of methane from coal mines: The foremost rationale is the enhancement of mine safety. Methane accumulates in various states within coal mines, contaminating the mine atmosphere, with the most hazardous scenario being its abrupt release. This can greatly amplify the potential for an explosion within the mines. Methane explosions stand out as perilous incidents, often resulting in the highest number of fatalities relative to other mining accidents. These explosions can also cause extensive damage, and the creation of toxic gases post-detonation contributes to additional subsequent harm and losses.

This paper delves into the mechanics underlying the outburst of coal gas, examining and managing the phenomenon of coal gas’s sudden discharge through lab-based research. Findings indicate that outbursts of coal gas can be forestalled on the experimented coal sample by lowering the pressure by 20% via degassing methods.

REFERENCES

[1] Aguado, M. B. D., & Nicieza, C. G. (2007). Control and prevention of gas outbursts in coal mines, Riosa–Olloniego coalfield, Spain. International Journal of Coal Geology, 69(4), 253-266.

[2] Alexeev, A., Revva, V., Alyshev, N., & Zhitlyonok, D. (2004). True triaxial loading apparatus and its application to coal outburst prediction. International Journal of Coal Geology, 58(4), 245-250.

[3] Beamish, B. B., & Crosdale, P. J. (1998). Instantaneous outbursts in underground coal mines: an overview and association with coal type. International Journal of Coal Geology, 35(1-4), 27-55.

[4] Cao, J., Dai, L., Sun, H., Wang, B., Zhao, B., Yang, X., . . . Guo, P. (2019). Experimental study of the impact of gas adsorption on coal and gas outburst dynamic effects. Process Safety and Environmental Protection, 128, 158-166.

[5] Fan, C., Li, S., Luo, M., Du, W., & Yang, Z. (2017). Coal and gas outburst dynamic system. International Journal of Mining Science and Technology, 27(1), 49-55.

[6] Hongwei, J., Qianting, H., & Yanbao, L. (2011). Failure mechanism of coal and gas outburst initiation. Procedia Engineering, 26, 1352-1360.

[7] Huang, W., Zhanqing, C., Jianhua, Y., Zhang, Y., & Min, Y. (2010). Failure modes of coal containing gas and mechanism of gas outbursts. Mining Science and Technology (China), 20(4), 504-509.

[8] Lama, R., & Bodziony, J. (1998). Management of outburst in underground coal mines. International Journal of Coal Geology, 35(1-4), 83-115.

[9] Litwiniszyn, J. (1986). Remarks concerning sudden rock-and-gas mass outbursts. Mining Science and Technology, 3(4), 243-253.

[10] Pan, X., Cheng, H., Chen, J., & Zhou, X. (2020). An experimental study of the mechanism of coal and gas outbursts in the tectonic regions. Engineering Geology, 279, 105883.

[11] Shang, S., Zhang, Q., Zhao, Y., Diao, Y., Yin, J., Che, Y., . . . Zhao, B. (2023). Experimental research of the geo-stress evolution law and effect in the intact coal and gas outburst process. Frontiers in Earth Science, 10, 1036165.

[12] Torano, J., Torno, S., Alvarez, E., & Riesgo, P. (2012). Application of outburst risk indices in the underground coal mines by sublevel caving. International Journal of Rock Mechanics and Mining Sciences, 50, 94-101.

[13] Wang, C., & Cheng, Y. (2023). Role of coal deformation energy in coal and gas outburst: A review. Fuel, 332, 126019.

[14] Yang, D., Chen, Y., Tang, J., Li, X., Jiang, C., Wang, C., & Zhang, C. (2018). Experimental research into the relationship between initial gas release and coal-gas outbursts. Journal of Natural Gas Science and Engineering, 50, 157-165.

[15] Zhang, E., Zhou, B., Yang, L., Li, C., & Li, P. (2023). Experimental study on the microseismic response characteristics of coal and gas outbursts. Process Safety and Environmental Protection, 172, 1058-1071.

[16] Zheng, J., Huang, G., Cheng, Q., Jia, J., & Cai, Z. (2022). A novel experimental apparatus for evaluating coal-and-gas outburst risk. Natural Resources Research, 31(1), 535-550.

[17] Zhou, A., Wang, K., & Wu, Z. (2014). Propagation law of shock waves and gas flow in cross roadway caused by coal and gas outburst. International Journal of Mining Science and Technology, 24(1), 23-29.

[18] Zhou, H., Yang, Q., Cheng, Y., Ge, C., & Chen, J. (2014). Methane drainage and utilization in coal mines with strong coal and gas outburst dangers: a case study in Luling mine, China. Journal of Natural Gas Science and Engineering, 20, 357-365.

[19] H. D. Cheng, E. Detournay, and Y. Abousleiman, ‘Poroelasticity, vol. 27’, *Theory and Applications of Transport in Porous Media Berlin: Springer*, p. 877, 2016.