

Prospect of Application of High Energy Photon Source in Coal Dust Explosion Research

Zhiling Fang^{1, 2, 3}, Zijing Shen^{1, 2, 3}, Jiahao Liu³, Longlong Yang⁴, Lunjing Yan^{1, 2*},
Meijun Wang^{1, 2}, Zhihong Li^{3*}, Liping Chang^{1, 2}

¹ State Key Laboratory of Clean and Efficient Utilization of Coal-based Energy, Taiyuan University of Technology, Taiyuan, Shanxi Province, 030024, China

² Key Laboratory of Coal Science and Technology, Ministry of Education, Taiyuan University of Technology, Taiyuan, Shanxi Province, 030024, China

³ Beijing Synchrotron Radiation Facility, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, 100049, China

⁴ State Key Laboratory of Explosion Science and Safety Protection, Beijing Institute of Technology, Beijing, 100081, China

Received September 21, 2025; Accepted March 4, 2026

Abstract

Coal dust explosion, as a violent physicochemical coupling phenomenon, not only threatens industrial safety but also profoundly impacts the environment and personal safety. The process is jointly regulated by the complex feedback mechanism among the pore structure of pulverized coal, chemical reactions and energy release. In recent years, researchers have utilized synchrotron radiation small-angle X-ray scattering (SAXS) technology in combination with an innovative dust explosion experimental platform to achieve in-situ real-time observation of the dynamic evolution of nano-pores during the explosion process for the first time at the Beijing Synchrotron Radiation Facility (BSRF), revealing key mechanisms such as the pore dilation-collapse cycle and the regulation of ignition delay. However, due to the limitations of the current light source flux, the temporal resolution of the experiment can only reach the millisecond level, which is still insufficient to capture the behavior of more transient nanoparticles. With the completion of the fourth-generation High Energy synchrotron photon source (HEPS), its ultra-high luminous flux will drive experiments into the microsecond and even nanosecond levels, providing new opportunities to reveal the fine processes, such as the generation and agglomeration of nanoparticles. In the future, the development of multimodal integration and complex systems research will provide stronger support for analysing the explosion mechanism of coal dust and verifying multi-scale models.

Keywords: Coal explosion; Pore evolution; Synchrotron radiation SAXS; In-situ characterization; High energy photon source.

1. Introduction

Coal dust explosion is a typical physicochemical coupling process that involves the rapid release of energy and drastic changes in temperature and pressure, and is extremely destructive in industrial production [1]. Therefore, in-depth analysis of the micro evolution mechanism of coal dust explosion and clarification of the relationship between key factors have become the core prerequisite for promoting the upgrading of industrial dust explosion prevention and control technology and reducing the incidence of safety accidents, which is of irreplaceable practical significance for ensuring the safe and stable operation of the whole industrial chain such as coal mining, processing, storage and transportation. In recent years, with the breakthrough development of synchrotron radiation technology, it has provided a new technical path for the microscopic study of dust explosions [2], especially the combination of small-angle X-ray scattering (SAXS) and in-situ experimental platforms [3], and the researchers have

achieved real-time observation of the dynamic evolution of nanoscale pore structure during pulverized coal explosion for the first time, revealing key mechanisms such as pore expansion-collapse cycles, ignition delay regulation, and multi-scale pore response [4], providing direct evidence for analyzing the nature of explosions at the nanoscale. However, due to the limited luminous flux (10^{11} phs/s) of the first generation of synchrotron radiation sources (BSRF), the temporal resolution of existing studies is only in the millisecond range, making it difficult to capture more transient nanoparticle behavior [5]. With the imminent completion of the fourth generation of high-energy photon sources (HEPS) by the end of 2025 [6], its ultra-high luminous flux (10^{15} phs/s) is expected to improve temporal resolution to the microsecond and even nanosecond level, providing new opportunities for elucidating the fine structural evolution of dust explosions, such as nanoparticle agglomeration. At the same time, advances in multimodal coupled technology and complex systems research [7] will further deepen understanding of explosive coupling mechanisms and lay the foundation for experimental verification of multi-scale models.

2. Coal dust explosion and its hazards

A coal dust explosion is a phenomenon in which a combustible gas mixture formed by coal dust in the air reacts violently in an instant [8]. As a typical physicochemical coupling process, coal dust explosion is accompanied by the rapid release of energy and drastic changes in temperature and pressure [9]. Due to their small size and large specific surface area, pulverized coal particles react with oxygen at an accelerated rate when suspended in air, making them highly susceptible to spontaneous combustion or ignition [10]. Under appropriate temperature and pressure conditions, the volume of the coal dust cloud expands rapidly, and gas combustion and thermal expansion can cause explosions, resulting in great destructive power [11].

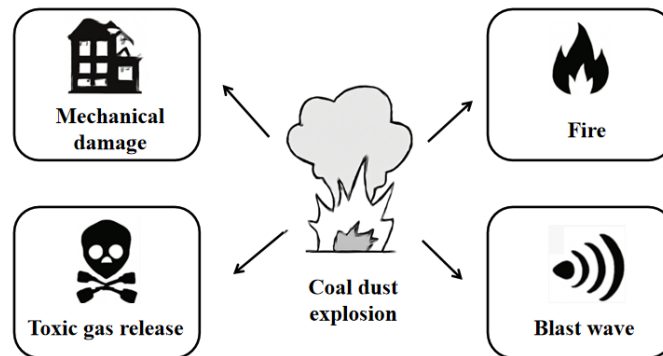


Figure 1. Hazards of coal dust explosion.

The hazards of coal dust explosions are not only reflected in the mechanical damage, fire, and high-temperature effects caused by the explosion itself, but also in the release of toxic gases, which can further cause long-term effects on the environment and human health [12]. Figure 1 illustrates the hazards of coal dust explosions, in which the shock wave can destroy surrounding buildings and cause casualties, while fires and coal dust flames can trigger broader disasters and lead to significant economic losses for coal mines and related industrial production facilities [13]. Therefore, coal dust explosions are not only a serious safety problem, but also a huge threat to the environment and society.

3. Interaction between pore structure and chemical reaction and explosive behavior of pulverized coal

In the process of coal dust explosion, there is a complex relationship between pore structure, chemical reaction and explosion behavior, and these factors interact with each other through positive and negative feedback mechanisms to determine the intensity and sustainability of the explosion.

The pore structure of pulverized coal plays an important role in chemical reactions and explosive behavior. Pulverized coal particles with higher porosity provide a larger specific surface area and facilitate the contact between oxygen and pulverized coal, thereby accelerating the progress of oxidation and pyrolysis reactions [14-15]. Larger pores can hold more gas, accumulating energy and further enhancing the intensity of the explosion. While pulverized coal with smaller pores may limit the diffusion of gases, slow down the speed of reactions, and inhibit the energy release of explosions [16].

The chemical reaction process also has a counter-effect on the pore structure and explosion behavior of pulverized coal. Pyrolysis and oxidation reactions not only release energy, but may also cause the expansion or rupture of pulverized coal pores, change the distribution and structure of the pores, and then affect the diffusion path and reaction rate of the gas [17]. The accumulation of gases and the increase in temperature during the reaction may accelerate the change of pores, forming a positive feedback mechanism, making the reaction more intense and enhancing the explosion intensity. Conversely, excessive pore expansion or rupture can limit reactant exposure, creating a negative feedback mechanism that slows the reaction rate and reduces explosion intensity.

The explosion itself will also have a feedback effect on the pore structure and chemical reaction of pulverized coal. In high-temperature and high-pressure environments, the pores of pulverized coal particles may change drastically, and the expansion or collapse of the pores directly affects the diffusion of gases, heat conduction, and the conduct of reactions, which in turn affects the intensity and duration of explosions [18]. The energy release during the explosion not only promotes the acceleration of the reaction, but also may lead to the destruction of pores, further change the microstructure of the pulverized coal, form a positive feedback loop, and intensify the progress of the explosion reaction.

Therefore, the interaction between pore structure, chemical reaction and explosive behavior during coal dust explosion is a dynamic feedback process, which includes both positive and negative feedback mechanisms. An in-depth understanding of this mechanism can help researchers more accurately grasp the microscopic mechanism of coal dust explosions and provide theoretical support for the formulation of effective prevention and control strategies.

4. In-situ research progress on the dynamic change of pore structure during pulverized coal explosion

As a typical multi-scale and multi-physics coupled violent reaction process, the intensity of pulverized coal explosion is not only controlled by macroscopic thermodynamics and chemical kinetics, but also closely related to the dynamic evolution of microscopic particle structures, especially nanopores [19]. It is difficult to achieve real-time observation of microscopic and mesoscopic pore changes on the order of milliseconds to nanoseconds by traditional methods, and only static analysis of explosive materials and products can be performed [20]. In terms of dynamic in-situ analysis, only in-situ studies of explosion pressure and flame [21] were realized, as well as in-situ studies of the slow-speed pyrolysis process of coal. In recent years, our research team has built an in-situ experimental platform with time-resolving capabilities with the help of high-throughput X-ray sources provided by synchrotron radiation and the high sensitivity of small-angle X-ray scattering SAXS technology [22].

The team has made key breakthroughs in synchrotron radiation SAXS experimental technology and platform innovation. A 20 L stainless steel spherical explosion-compatible chamber with a single-crystal diamond window is designed to provide both high-pressure resistance and high X-ray transmittance [23]. The Eiger 1M detector and the innovative dual-thickness attenuator technology [24] were used to achieve dynamic signal acquisition and normalization with 10 ms level time resolution. A millisecond-level timing control system was developed to ensure the precise linkage between powder spraying, ignition, and data acquisition [3], and fuzzy effect processing for thick and thin samples [25] and ectopic absolute intensity calibration methods [26] were developed to provide theoretical guarantee for dynamic process analysis.

Regarding the key findings of pore dynamic evolution, the study reveals that high-carbon pulverized coal (such as coking coal) exhibits a pore expansion-collapse cycle during the explosion process: the porosity increases rapidly from 2.4% to 5.1%, and then collapses rapidly due to high-temperature sintering, which is directly related to the release of explosion energy. The ignition delay time has a significant regulatory effect on pore evolution: under the condition of short delay (80 ms), the dust is uniformly suspended, the pore expansion is more significant (specific surface area reaches $176.37 \text{ m}^2/\text{cm}^3$), and the explosion strength is higher. However, the long delay (120 ms) leads to particle settling and limited pore evolution [19]. The SAXS technique also reveals the differential response of multiscale pores, where micropores of $5 \text{ nm} <$ dominate the gas diffusion pathways.

In terms of the coupling mechanism between structure and explosion, a quantitative feedback model is proposed [4]. The positive feedback path is as follows: rapid pore expansion \rightarrow increased specific surface area \rightarrow accelerated release of volatile components \rightarrow strengthened gas phase reaction \rightarrow rapid increase in pressure. The negative feedback path is manifested as pore collapse \rightarrow gas channel interruption \rightarrow reaction termination, \rightarrow pressure decay. The study further introduced the integral invariant Q as a quantitative index of pore connectivity, and found that it was significantly positively correlated with the explosion index (K_{st}).

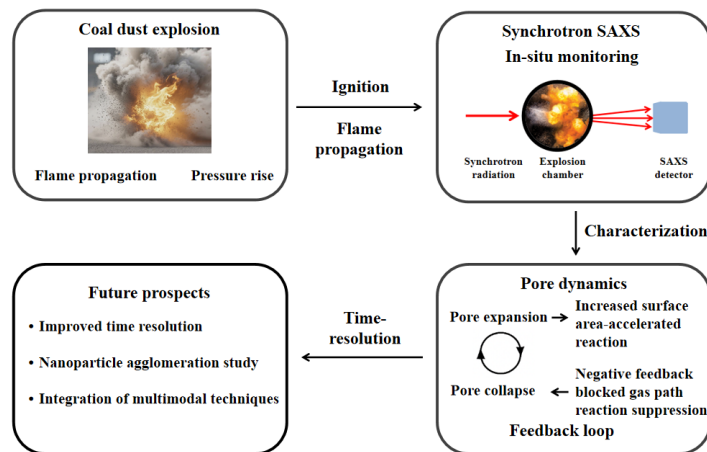


Figure 2. Application of synchrotron radiation SAXS in pulverized coal explosion research.

Figure 2 shows the application of synchrotron radiation SAXS in the study of coal dust explosions, although these studies apply SAXS technology to nanoscale dynamic structure detection of pulverized coal explosions for the first time, achieving a triple breakthrough of "in-situ and time resolution and structural analysis", but it is only a preliminary study. Due to the limited synchrotron radiation luminous flux (BSRF: 10^{11} phs/s), the time resolution is only 10 ms, but the overall approximate characteristics of the pore structure change have been preliminarily revealed. If the luminous flux can be further improved, the temporal resolution will be improved to reveal the subtle characteristics of structural changes.

5. Application prospect HEPS in the study of coal dust explosion

The temporal resolution of dust explosion in-situ experiments depends on luminous flux, detection velocity, and explosion velocity, with luminous flux being the biggest constraint. With high luminous flux, the detector can obtain a sufficiently statistical scattering signal in a short period of time, resulting in high temporal resolution [27]. The in-situ study of dust explosions is based on the first generation of BSRF. Beijing is building the world's brightest light source, the fourth-generation HEPS, which will be completed and put into trial operation by the end of 2025. The pink light small-angle X-ray scattering station [28] will have a luminous flux of 10^{15} phs/s , which can significantly improve the temporal resolution, and is expected to

carry out microsecond/nanosecond time-resolution studies to obtain fine structural information during dust explosions, such as nanoparticle agglomeration and other transient phenomena.

At present, there are still certain challenges in carrying out in-situ research on dust explosions on fourth-generation synchrotron radiation sources. In addition to the need to upgrade the experimental platform to accommodate high-resolution experiments, it is also necessary to explore methods for parsing complex data. For example, SAXS itself is difficult to distinguish whether the scatterers it detects are particles or pores, because according to the Barbinette optical interaction principle, the scattering of particles and pores is complementary [29], and it needs to be comprehensively judged based on specific physicochemical characteristics or other characterization methods. Although dust particles are typically in the tens to hundreds of microns in size, they are not within the detection range of SAXS. However, nanoscale particles suitable for SAXS detection occur during the generation and explosion of dust. These tiny particles have a large specific surface area and are not stable on their own and will quickly agglomerate to reduce their energy. On low-flux first-generation synchrotron radiation sources (BSRF), 10 ms time-resolution may not capture nanoparticle agglomeration, but nanoscale pores can be detected inside large particles and inside small particle aggregates. At HEPS, the generation and aggregation process of nanoparticles may be captured, and the signal screening of nanoparticles and nanopores will be a major challenge and deserve in-depth study.

While applying HEPS to improve temporal resolution, multi-modal coupled technologies (such as SAXS, infrared, imaging, etc.) can also be introduced to apply to the explosion behavior of more complex multi-component dust systems or additive systems, promote coupling with numerical simulation, and establish an experimental verification platform for multi-scale explosion models.

6. Summary

The study of coal dust explosions has made significant progress, driven by synchrotron radiation technology, especially the combination of SAXS and an in situ experimental platform, which has enabled real-time observation of the dynamic evolution of nanopores during the explosion process for the first time. It is found that the expansion-collapse cycle of pore structure, the influence of ignition delay time, and the dominant role of micropores are closely related to the explosion intensity. However, current research is limited by the performance of light sources, and temporal resolution remains insufficient to resolve faster transient processes. The completion of the fourth-generation HEPS will greatly improve the experimental capacity and make microsecond/nanosecond observations possible, while the expansion of multimodal coupled use and complex systems will further improve the explosion model. In the future, the combination of high temporal resolution technology and multi-scale analysis is expected to provide a more solid scientific basis for accurate prediction and prevention and control of coal dust explosions.

Acknowledgments

This work was supported by the State Key Laboratory of Explosive Science and Safety Protection of Beijing Institute of Technology (KFJJ24-14M), the Shanxi Provincial Scientific and Technological Achievements Transformation and Guidance Project (202304021301042), and the Shanxi Provincial Fund-raising Scientific Research Project for Returning Students (2024-039).

References

- [1] Zhang XL, Chen G, Xu S, Yang WT, Gao JD. Comparative study on dust explosion accident statistics and management system between China and the United States(in Chinese). *Journal of Safety and Environment*, 2023; 23(08):2769-2779.
- [2] Mai ZH. *Synchrotron Radiation Source and Its Applications*. Science Press (in Chinese), 2013.
- [3] Wu HJ, Li WM, Sun YF, Zhang ZB, Qin QF, Han QF, Wei SJ, Li ZH, Zhao YX, Cao X. Preliminary development of a dust explosion equipment for time-resolved SAXS experiment with synchrotron radiation. *Nuclear Instruments and Methods in Physics Research Section B*, 2024, 549: 165265. <https://doi.org/10.1016/j.nimb.2024.165265>

- [4] Ji XL, Liu JH, Wu HJ, Yang LL, Li WM, Sun YF, Qin QF, Li ZH, Dong LL, Wang YY, Zhao YX, Cao X, Li DF. In situ study of the effect of ignition delay time on the lignite dust explosion using synchrotron radiation time-resolved SAXS. *Fuel*, 2025; 398:135569. <https://doi.org/10.1016/j.fuel.2025.135569>
- [5] Wu HJ, Liu JH, Li ZH. Synchrotron radiation small-angle x-ray scattering method: challenges and potential in dust explosion research (in Chinese). *The Journal of Light Scattering*, 2025; 37(2): 159-171.
- [6] Yi J, Gang X, Qing Q. The HEPS project. *Journal of Synchrotron Radiation*, 2018; 1611-1618.
- [7] Wang YL, Wang BB, Zang YC, Zhang JQ, Song YJ, Yang SH. Prediction model for chemical explosion consequences via multimodal feature fusion. *Journal of Cheminformatics*, 2025; 17, 118. <https://doi.org/10.1186/s13321-025-01060-x>
- [8] Cashdollar K L. Overview of dust explosibility characteristics. *Journal of Loss Prevention in the Process Industries*, 2000; 13:183-199. [https://doi.org/10.1016/S0950-4230\(99\)00039-X](https://doi.org/10.1016/S0950-4230(99)00039-X)
- [9] Cao WG, Huang LY, Liang JY, Miao N, Rao GN, Pan F. Research on characteristic parameters of coal dust explosion in a spherical sealed container (in Chinese). *Journal of China University of Mining and Technology*, 2014, 43(1): 113-119.
- [10] Nie BS, Wang XT, Gong J, Yin PP, Peng C. Research progress on explosion characteristics and explosion suppression methods of gas and coal dust (in Chinese). *Safety and Security*, 2021, 42(01):1, 1-15.
- [11] Yu HK, Wang C, Pang L, Chen DP. . Experimental study on influencing factors of ignition sensibility of coal dust cloud (in Chinese). *Transactions of Beijing Institute of Technology*, 2020, 40(6): 602-608.
- [12] Lin S, Liu ZT, Qian JF, Li XL. Comparison on the explosivity of coal dust and of its explosion solid residues to assess the severity of re-explosion. *Fuel*. 2019. 251: 438446. <https://doi.org/10.1016/j.fuel.2019.04.080>
- [13] Sahu A, Mishra DP. Prevention and suppression of coal dust explosion in underground coal mines: Role of rock dust type, particle size, proportion, concentration, and thermal properties. *Advanced Powder Technology*, 2024; 35(2), 104343.
- [14] Xie F, Li ZH, Wang WJ, Li DF, Li ZZ, Lv BL, Hou B. In-situ SAXS study of pore structure during carbonization of non-caking coal briquettes. *Fuel*; 2020; 262, 116547. <https://doi.org/10.1016/j.fuel.2019.116547>
- [15] Li X , Fan YQ, Li ZH. In-situ SAXS-WAXS study on preparation of activated carbon from anthracite. *Petroleum and Coal*, 2025; 67(2): 358-371.
- [16] Nie BS, Yang LL, Wang C, Huang JX. Soot characteristic and formation mechanism in the process of gas explosion (in Chinese). *Transactions of Beijing Institute of Technology*, 2017, 37(4): 424-429.
- [17] Sun YF, Zhao YX, Liang Y. Impact of coal composition and pore structure on gas adsorption: a study based on a synchrotron radiation facility. *Greenhouse gases: science and technology*, 2020; 10(1): 116-129.
- [18] Nie BS, Zhang H, Gong J, Peng C, Yang LL, Yan HW, He XQ. Macro and micro four-stage reaction mechanism of pulverized coal explosion (in Chinese). *Journal of China University of Mining and Technology*, 2023, 52(06): 1129-1145.
- [19] Wu HJ, Liu JH, Ji XL, Li WM, Yang LL, Sun YF, Qin QF, Li ZH, Cao X, Zhao YX. Preliminary application of synchrotron time-resolved SAXS in in-situ study of dust explosion. *Fuel*, 2025; 404:136194. <https://doi.org/10.1016/j.fuel.2025.136194>
- [20] Luo L, Liu JX, Zhang YC, Zhang H, Ma JF, You YL, Jiang XM. Application of small angle X-ray scattering in evaluation of pore structure of superfine pulverized coal/char. *Fuel*, 2016; 185(1): 190-198. <https://doi.org/10.1016/j.fuel.2016.07.111>
- [21] Cao WG, Xu S, Liang JY, Gao W, Pan F, Rao GN. Characteristics of flame propagation during coal dust cloud explosion (in Chinese). *Explosion and Shock Waves*, 2014, 34(05): 586-593.
- [22] Glatter O, Kratky O. Small angle X-ray scattering [M]. Academic Press Inc, New York, 1982: 17-52.
- [23] Li ZH, Zhao YX, Cao X, Wu HJ, Han QF, Wei SJ, Zhang ZB, Li WM, Sun YF, Qin QF. dust explosion microscopic dynamics research device: China 202321304303.3. 2023. 12. 08.
- [24] Wu HJ, Li ZH. A new dual-thickness semi-transparent beamstop for small-angle X-ray scattering. *Journal of Synchrotron Radiation*, 2024; 31(5): 1197-1208.
- [25] Wu HJ, Chen RC, Li ZH. Optimization of sample thickness for small-angle X-ray scattering (SAXS). *Instrumentation Science and Technology*, 2022; 51(1): 84-98.

- [26] Fan YQ, Chen RC, Shang XX, Wu HJ, Yang CM, Fan HL, Li ZH, Chen JG, Li DF. Absolute Intensity Calibration of Samples at Variable Sample to Detector Distances in Small Angle X-Ray Scattering (SAXS) [J]. *Instrumentation science and technology*, 2024, 52, 6: 702-710.
- [27] Ma LD, Yang FJ. Introduction to synchrotron radiation applications (in Chinese). Fudan University Press, 2005.
- [27] Ma LD, Yang FJ. Introduction to Synchrotron Radiation Applications. Fudan University Press, 2005.
- [28] Li ZH, Jia QJ, Li M. Conceptual design of a simple small angle X-ray scattering (SAXS) beamline. *Instrumentation Science and Technology*, 2021; 49(5): 560-570.
- [29] Pei GW, Zhong WL, Yue SB. X-ray diffraction of single crystals, polycrystals, and amorphous substances (in Chinese). Shandong University Press, 1989: 386-445.

To whom correspondence should be addressed: Zhihong Li, Beijing Synchrotron Radiation Facility, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, 100049, China, E-mail: lzh@ihep.ac.cn and Lunjing Yan, State Key Laboratory of Clean and Efficient Utilization of Coal-based Energy, Taiyuan University of Technology, Taiyuan, Shanxi Province, 030024, China, E-mail: yanlunjing@tyut.edu.cn