Available online www.jsaer.com

***Journal of Scientific and Engineering Research*, 2024, 11(5):188-198**

Research Article

ISSN: 2394-2630
CODEN(USA): JSERBR

Research Status and Prospects of Hydraulic Punching Technology in China

SUN Haoquan

College of Safety Science and Engineering, Henan Polytechnic University, 454003, Jiaozuo, Henan, China
Email: 3200395749@qq.com

Abstract As coal mining in my country gradually moves into deeper areas, problems such as high gas pressure and low air permeability in coal seams have become more and more prominent, seriously affecting the safe mining of coal mines. In order to improve the gas permeability of coal seams and strengthen gas drainage, hydraulic punching technology has gradually become a mainstream pressure relief and permeability enhancement technology with its advantages of high efficiency and cleanliness. Based on the survey of a large number of literature, the relevant theories of water jet rock breaking mechanism are systematically summarized, and the characteristics and shortcomings of different theories are pointed out; punching methods including punching method, punching pressure, drilling inclination angle, etc. are introduced. The influence of hole process parameters on the effect of hydraulic punching; the on-site application of hydraulic punching is sorted out, and on this basis, the development trend of future hydraulic punching technology is prospected. It is believed that it is necessary to continuously deepen interdisciplinary theoretical research and further reveal the water punching effect. The mechanism of jet rock breaking and hydraulic punching technology will develop towards the integration and intelligence of punching equipment and the combination of anti-reflection measures.

Keywords hydraulic punching, punching parameters, water jet rock breaking, combined antireflection

Introduction

China has one of the richest gas reserves in the world. The amount of shallow gas geological resources with a buried depth of 2000 m is about 36.81 trillion m^3, which is equivalent to 38 trillion m^3 of conventional natural gas resources on land, and the total amount of recoverable gas resources is about 10 trillion m ~ 3, of which the gas geological resources of 1000 m, 1000 m, 1500 m and 2000 m account for 38.8%, 28.8% and 32.4% of the total gas resources in China, respectively, but the coal seam conditions in most mining areas are complex. It has the characteristics of low permeability ($< 0.001 \times 10^{-15}$m$^{2)}$, high gas pressure (up to 6.5MPa), soft coal ($f < 0.5$), structural development and so on. Under this background, China's coal development is still rapidly transferring to the deep at the rate of 10m to 25m per year. There are 47 mines with a depth of more than km, and more than 30 km mines will be built in the next 5-10 years [4-6]. With the continuous advance of coal mining to the deep [7], the difficulty of gas extraction is increasing, and the danger of coal and gas outburst is increasing, which seriously restricts the safe and efficient coal mining [8-11]. Under the new situation, how to improve coal seam permeability and promote efficient coal seam gas extraction has become a strategic issue to promote the safe mining of coal resources and ensure the sustainable supply of national energy.

In recent years, China has carried out a lot of research on the problem of low permeability of coal seams. Hydraulic punching [12-15] hydraulic cutting [16-19] and hydraulic fracturing [20-24] have been widely used in pressure relief and permeability enhancement of low permeability coal seams and enhanced gas extraction in coal seams [20-26] because of their high efficiency and clean advantages. Among them, the hydraulic punching technology was first put forward by the Makaiev Coal Mine Safety Research Institute of the Soviet Union [27]. Using the technology of opening pressure relief trough by water pump, experiments were carried out in the outburst dangerous coal seam of Kirov Coal Mine of Donetsk Coal Administration Bureau. It shows a good anti-outburst effect [28]. The research on hydraulic punching technology in China began in the late 1950s, in which Nantong Mining Bureau located in Chongqing first carried out the research on hydraulic punching and outburst prevention [29]. Since then, hydraulic punching technology has been continuously developed. it has been widely popularized all over the country. Based on this, the research status of hydraulic punching technology in China is combed, and the key points and development trend of hydraulic punching technology in the future are prospected

Mechanism of Pressure Relief and Permeability Increase by Hydraulic Punching

Hydraulic punching technology is the use of high-pressure water jet to impact the coal body, resulting in the fragmentation of the coal body, inducing small outburst in the borehole, and the coal debris is discharged from the coal body with the flow of water, so that the stress of the coal body around the hole is also released. the permeability of coal body is further improved, and the difficulties of gas drainage in high gas and low permeability coal seam are effectively solved. However, because water jet rock breaking has the characteristics of high sensitivity of nozzle structure, complex crushing mode and mechanism, and high strain rate of brittle rock, it is difficult to accurately describe the internal mechanism and physical breaking process of water jet rock breaking. Thus, it seriously restricts the further development of hydraulic punching and other hydro-technology [31]. In recent decades, many scholars and experts have studied the rock breaking mechanism of water jet from different angles and different methods, and achieved fruitful results. it mainly includes: dense core-split tension breaking theory, stress wave breaking theory, tensile-water wedge breaking theory, cavitation (cavitation) breaking theory.

Dense core-split tension rock breaking theory

Dense core-split rock breaking theory (figure 1) [31-36]: using Hertz contact theory, the rock breaking process of water jet is simplified as a rigid body with a certain speed pressed into a semi-infinite body of rock, and the end face of the jet acts on the surface of the rock. as a result, the rock near the end face is subjected to shear stress and tensile stress, because the tensile strength of the rock is much less than the compressive strength. Therefore, when the tensile stress and shear stress of the rock near the end face are greater than its tensile and shear strength, the rock breaks, forms a crack and gradually extends to the end face of the jet, while the rock at the end face of the jet is mainly subjected to compressive stress. the stress concentration at the end plane forms a dense core composed of rock powder, which acts as a "rock cushion" between the undisturbed rock and the rock. With the continuous action of the water jet, the volume of the dense core becomes smaller and accumulates energy. when the stored energy reaches a certain degree, the volume of the dense core increases and the energy is released, which makes the surrounding rock produce tangential tensile stress. when the tensile stress is greater than the tensile strength of the rock, the rock produces radial fissures, rock powder wedges into the fissures, promotes the further extension of the cracks, and splits the rock in the direction of the free surface with less resistance. Causing the rock to break.

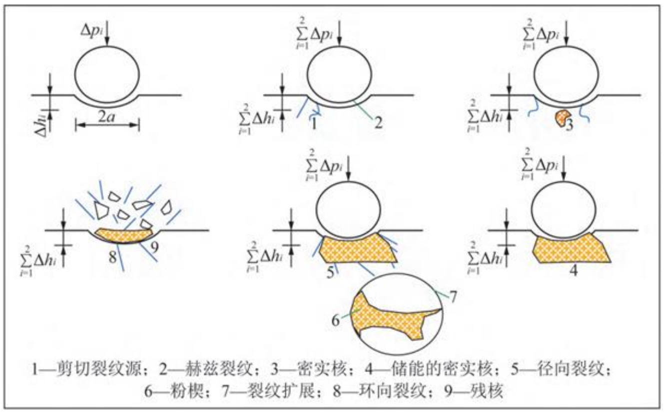

Figure 1: dense core-splitting rock breaking mechanism

Stress wave breaking theory

Stress wave breaking theory [37-41]: it is considered that when the water jet hits the rock, the high pressure of the water jet produces a strong compression wave on the rock surface, and the impact zone of the rock surface is under the absolute pressure, also known as the water hammer pressure. After the fluid hits the rock surface, it will flow radially outward, resulting in a sharp drop in the pressure in the impact zone, from water hammer pressure to stagnant pressure, and the strong compression wave acting on the rock is reflected, forming a strong radial tension in the rock. When the radial tension exceeds the tensile strength of the rock, the rock produces cracks. With the continuous impact of the water jet, the rock is subjected to the repeated action of strong compression waves, and finally broken.

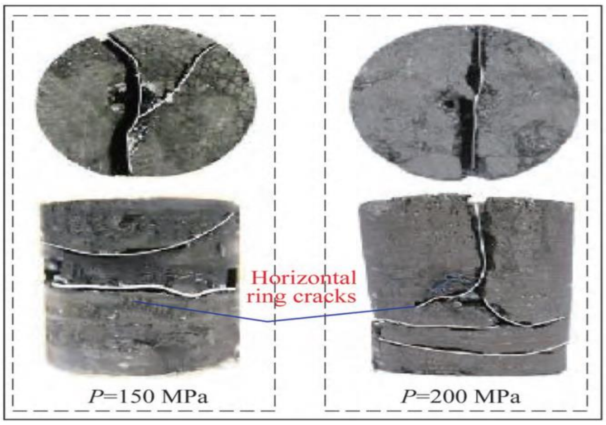

Figure 2: Water jet destroys coal and rock

Tension-water wedge crushing theory

Tension-water wedge breaking theory (Fig. 3) [32-42-44]: this theory simplifies the impact force of water jet to the concentrated force acting on the plane of rock half-space elastomer. When the water jet acts on the rock, the stress exceeds the tensile and shear strength of the rock, the rock begins to produce cracks. With the extension and interpenetration of the fracture, the water jet enters the crack, and the fluid compression causes the tensile stress concentration at the crack tip, resulting in the rapid expansion of the fracture, and its rock breaking principle is similar to that of the wedge, so this theory is called tension-water wedge crushing theory.

Cavitation (cavitation) breaking theory

Cavitation (cavitation) fragmentation theory (Fig. 4) [32jets 45-50]: it is considered that there are a large number of bubbles in the water jet. When the fluid hits the rock surface, the bubbles are strongly compressed and burst, forming a high-energy microjet. The rock is broken by the impact of high-speed microjets. The above theory expounds the rock-breaking mechanism of water jet from different angles, but there are also some shortcomings. The dense core-split tension rock breaking theory expounds the rock breaking process of water jet from the point of view of rock strength performance.

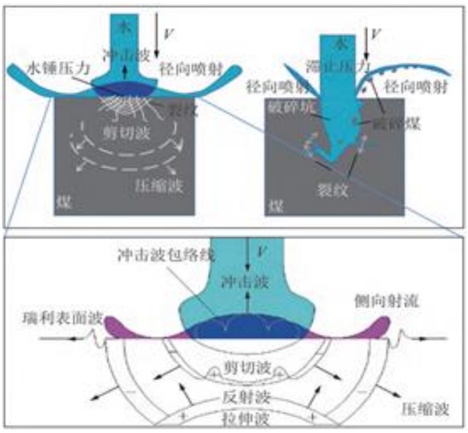

Figure 3: Tensile-water wedge crushing mechanism

Figure 4: Mechanism of cavitation effect of ultra-high pressure water jet

However, it is ignored that water jet rock breaking is a dynamic process, which involves liquid-solid coupling, the strength properties of rock will change accordingly, and the development of fractures is constantly changing in time and space, this theory cannot explain the above phenomena, so it needs to be further improved. The tension-water wedge breaking theory also has some shortcomings. When the water jet hits the rock, there will also be cracks in the vertical direction of its action surface, but these cracks are not invaded by water, so this phenomenon contradicts this theory. The similarity between this theory and the dense core-split tensile rock theory is that the development mode of the fracture is affected by the tensile stress concentration at the crack tip. The difference is that the tensile stress concentration at the crack tip of the dense core-splitting rock theory is caused by the rock powder wedging into the fracture when the energy of the dense core is released. Moreover, like the dense core-split rock breaking theory, the tension-water wedge breaking theory ignores the liquid-solid coupling and can not explain the dynamic change of the crack without the action of the water jet. the stress wave breaking theory can explain the annular crack caused by water jet impacting rock, but ignores the effect of fluid on fracture propagation. The cavitation (cavitation) fragmentation theory focuses on the influence of high-speed microjet on rock caused by the collapse of bubbles in water jet, which can explain the generation of irregular pits on the surface of impacted coal, but it is not convincing enough for the generation and development of cracks. In addition, the rock performance characteristics used in the study of the above theory are different from the real coal bodies, and in practice, coal seams often contain gas gas. therefore, hydraulic measures such as hydraulic punching involve gas-solid-liquid three-phase coupling in the application, and its crushing mechanism is more complex. In a word, the improvement of the rock breaking mechanism of water jet needs to further consider the dynamic mechanical properties of impacted rock, the spatio-temporal evolution of cracks, and the three-phase coupling of gas-solid-liquid.

Research status of hydraulic punching Technology

Research status of the influence of different process parameters on punching effect

Different process parameters have a great influence on the effect of hydraulic punching. It mainly includes: punching mode, punching pressure, drilling inclination, nozzle parameters, rotational speed, hole layout, coal output and so on. Taking the hydraulic punching test of Zhaozhuang Coal Mine as the engineering background, JiabaoZ [51] monitored and analyzed the relationship between coal water content around borehole blockage and gas drainage effect, and considered that under the condition of the same amount of coal produced by punching, different punching modes lead to great differences in punching influence radius. Xie,S. [52] put forward the method of using intermittent hydraulic punching to extract gas from coal seam, which was verified by COMSOL numerical simulation and field practice. The results show that intermittent hydraulic punching can significantly improve gas concentration and discharge purity. Yang Tenglong [53] and others carried out engineering practice by taking the amount of coal washed out and the effective influence radius under different punching parameters as the investigation index, and found that with the increase of punching pressure and drilling inclination, the amount of coal washed out from a single hole and the effective influence radius increased, but the growth rate decreased. Ma Heng [54] and others analyzed and studied the piercing characteristics of high-pressure air jet and the law of coal breaking under the combination of jet parameters. The results show that among the three factors affecting the experimental results, the jet pressure has the greatest influence, the impact target distance takes the second place, and the nozzle specification has the least influence on the experimental results. Lu Yiyu [55] thinks that the crushing hard rock performance of pressurized pulsed water jet increases at first and then decreases with the increase of nozzle diameter, and the axial velocity of jet increases with the increase of jet pressure, but the energy loss increases due to the intensification of gas and liquid energy exchange. MinR [56] et al used numerical simulation and field experiments to study the influencing factors of hydraulic punching, and found that with the increase of punching water pressure, the plastic zone area increases synchronously, and the punching water pressure and plastic zone area meet the positive correlation. Chen Shuliang [57] adopted the physical experiment method to punch the cement mortar block, and found that with the increase of the punching pressure, the punching depth increases linearly, but there is an optimal distance between the punching target distance and the punching depth has a limit depth. Wang Feng [58] and others have studied the coal flushing amount and gas drainage effect of different angle boreholes under the same conditions. the results show that the coal flushing amount and gas drainage effect of hydraulic punching holes increase with the decrease of drilling angle. Zhao Jiangnan [59] summarized the characteristics and effects of various nozzles for hydraulic punching. Through theoretical analysis and calculation derivation, Chai Xijun [60] obtained the calculation formulas of nozzle diameter, efficiency and acting force, and analyzed the influence of nozzle shrinkage angle and length-diameter ratio on the injection effect by using numerical simulation software. it is considered that the nozzle diameter is the key factor affecting the hydraulic punching effect, and when the shrinkage angle is 10 °~ 15 °and the aspect ratio is 2: 3, the hydraulic punching effect is the best and the efficiency is the highest. Rose [61], Rajaratnam [62], Chigier and Chervinsky [63], Farokhi [64] hold that the mean velocity of a swirling jet is self-similar, and the width of the jet and the flow rate of entrainment fluid increase with the increase of the swirl number. Tao Yunqi [65] carried out hydraulic punching tests under different rotational speed conditions, compared the evolution law of gas pressure in the process of coal seam gas drainage before and after punching, and analyzed the influence of punching on the standard range of coal seam gas extraction. Based on the mechanism of hydraulic punching pressure relief and permeability increase, Wang Qingguo [66] proposed to adopt the extraction method of cooperative interval grid arrangement of hydraulic punching holes and ordinary pre-pumping holes to carry out efficient extraction. Liu Ting [67] studied the judgment criteria and optimization methods of the key process parameters of hydraulic punching. It is considered that when the extraction time is constant, the residual gas content in coal seam decreases gradually with the increase of punching coal output, but due to the increase of stress concentration between holes, the residual gas pressure decreases at first and then increases. The optimal coal output of punching decreases with the increase of ground stress, and increases with the increase of cohesion, gas pressure and hole spacing. Ren Peiliang [68] studied the effect of hydraulic punching coal flushing rate on the extraction effect. It is considered that with the increase of coal seam flushing rate, the coal seam gas content decreases and the higher the coal seam flushing rate, the greater the reduction of coal seam gas content, the better the effect of coal seam gas pre-drainage. Hui Yubo [69] found that the amount of hydraulic punching coal has a more significant effect on the deformation of coal slope than the distance between boreholes. Through the industrial test of hydraulic punching pressure relief pumping technology, Tao Yunqi et al preliminarily determined the optimal coal flushing quantity of hydraulic punching and the borehole inclination angle which is favorable for punching, and considered that the borehole inclination angle of 40 °~ 70 °is the most favorable for punching. Up to now, although many studies have been done on hydraulic punching process parameters at home and abroad, many important conclusions have been drawn, but the indexes and specifications that can be used to guide hydraulic punching technology have not been systematically summarized. The priority of various process parameters on punching effect is not clear, so it is still necessary to further improve the influence of different process parameters on punching effect in order to better guide coal mine safety production.

Research status of field application of hydraulic punching

Wei Jianping et al. [71] carried out hydraulic punching experiments in Yi'an Coal Mine, the effective radius of influence after punching reached 6.5 meters, and the number of boreholes in each drilling site was reduced from 20 to 14. Zhang Mingjie et al. [72] carried out a field test in Hebi Zhongtai Coal Industry Co., Ltd. the average amount of coal washed out from the coal hole is 1.3t/m, the extraction time is 60 days, and the extraction influence radius is 5.1m. He Jun et al. [73] analyzed the effective influence radius of Xintun coal seam after hydraulic punching, which shows that the effective influence radius after hydraulic punching is 8m. After punching, the air permeability of the coal seam is greatly improved. Liu Yong et al. [74] hydraulic gas pre-drainage was carried out in Shimen of the No. 655 track of Heshan Coal Mine. The coal output from a single hole was 38 tons. After punching, the gas drainage concentration and extraction flow rate were increased by 315 times, and the time for Shimen pre-extraction to reach the standard was shortened to less than three months. Wang Zhaofeng et al. [75] carried out hydraulic punching in Luobu'an Coal Mine, Jiahe County, and the effect is remarkable. The equivalent pore diameter of drainage borehole is increased by 13.38 times, the effective influence radius of borehole drainage is increased by 2 to 3 times, the gas pre-drainage concentration of single hole is increased by 4 to 5 times, and the drainage attenuation period is increased by more than 3 times. Liu Yingzhen et al. [76] carried out hydraulic punching experiments in Shoushan No. 1 Coal Mine, the total amount of gas drainage in the roadway increased by 2.58 times, the dynamic phenomenon disappeared, the residual gas content and pressure decreased below 6.8m3/t and 0.56MPa respectively, which were lower than the critical value, the extraction time was shortened from 90,180d to 2000d, and the monthly footage of coal roadway was doubled. Liu Yanwei et al [77] carried out hydraulic punching at the 11124 working face of Pan No.2 Coal Mine of Huainan Mining Group. The pressure relief and permeability increasing effect of hydraulic punching measures was obvious, the gas volume fraction increased from 7.8% (average) before punching to 56.9% (average) after punching, and the initial velocity of gas emission from boreholes decreased from 24.2L/min (average) before punching to 2.28L/min after punching. It is 90.57% lower than before. Tan Dongsheng [78], Xu Dongsheng [79] and Li Lei [80] also carried out hydraulic punching experiments in the field. After punching, the gas permeability of coal seam was significantly improved, and the efficiency of gas drainage was greatly improved. In addition, with the continuous deepening of hydraulic punching technology, various compound punching technologies have also been developed [30]. Such as "drilling-punching" integrated technology [81jue 82], "drilling-punching-cutting" integrated technology [83pr 84], "hydraulic fracturing-hydraulic punching" combined antireflection technology [85-88], "hydraulic punching-presplitting blasting" [89je 90] compound antireflection technology and so on. To sum up, the effect of hydraulic punching technology is outstanding in practical application, and it has the advantages of obvious pressure relief effect and high gas drainage efficiency. This technology is often used in the soft coal seam with high gas and low permeability, but the phenomena of spraying hole, blocking hole and collapsing hole often occur in the process of punching, and due to the erosion and softening effect of water flow, the surrounding rock of roadway is easy to cause instability, so it is necessary to further improve the safety of hydraulic punching technology. Secondly, hydraulic punching technology needs to use a lot of water, which is easy to cause muddy working face, difficult wastewater treatment and other problems.

Prospect of hydraulic punching technology

Deepen the theoretical research of cross-discipline

Gas occurs in the coal seam, mostly in the adsorption state, accounting for 80%, accounting for 90%. When the geological environment changes, the adsorbed gas can be converted into free gas and migrate in holes and fissures. In the process of hydraulic punching and coal breaking, high-pressure water jet acts on the coal seam, resulting in holes and a large number of cracks in the coal seam, resulting in the decrease of gas pressure in the surrounding coal. On the one hand, the adsorbed gas is desorbed due to the decrease of partial pressure. On the other hand, water flow will invade the coal seam, which can not only drive part of the gas, but also block the gas migration channel, so as to restrain gas desorption. Therefore, the gas-liquid-solid multiphase coupling is involved in the process of hydraulic punching, the coal breaking mechanism is more complex, the experimental cost is higher, and the downhole conditions are different, and the conclusions drawn are not universal, which makes the theoretical research lag behind the engineering practice and limits the development of punching technology. Hydraulic punching technology is a systematic project, which involves rock mechanics, gas geology, fluid mechanics, physics, chemistry and other disciplines from theory to practice. It is necessary to deepen the interdisciplinary theory, use numerical simulation, physical experiments, field experiments and other methods to reveal the coal-breaking mechanism of water jet, break through the bottleneck of hydraulic punching technology, and further improve hydraulic punching technology.

Integrated and intelligent punching equipment

Hydraulic punching in underground usually requires drilling first and then punching. Drilling equipment and punching equipment are not common. In the complex underground environment, it is necessary to ship and replace equipment back and forth, and it is difficult to transport and arrange the equipment. And the working environment continues to deteriorate with the impact of water, affecting the safety of underground miners. Therefore, in order to reduce the operating frequency of employees, ensure the safety of employees and improve the efficiency of piercing, it is necessary to realize the integration and intelligence of piercing equipment. Combine the theoretical research with the punching equipment organically, optimize the structure and material of the equipment, improve the punching efficiency, and develop auxiliary transportation and drainage devices to facilitate the handling of the equipment and reduce the influence of effluent on the working face. The intelligent punching equipment is realized by using modern technology, the dynamic changes of stress, strain and gas pressure in punching coal seam are fed back by intelligent system, and the punching pressure and punching angle are adjusted automatically to realize efficient hydraulic punching. Promoting the integration and intelligence of punching equipment is the key to respond to the national call, ensure the stable and safe supply of energy, and improve the supporting force of mine green development, and it is also the only way for the development of mine intelligence in the future.

Combination of antireflection measures

There are many kinds of anti-penetration technology of coal seam, in addition to hydraulic punching, there are mining protective layer, surface hydraulic fracturing, downhole hydraulic fracturing, deep-hole controlled presplitting blasting, hydraulic cutting and so on. However, each anti-penetration technology has its limitations. How to give full play to the advantages of each technology and learn from each other is the development trend of coal seam anti-penetration technology in the future. The combination of anti-permeability measures is to evaluate the coal seam as a whole and implement different anti-permeability measures according to the characteristics of coal seams in different regions, such as hydraulic fracturing-hydraulic punching, hydraulic punching-pre-splitting blasting and so on. the advantages of various measures complement each other to relieve pressure and increase permeability of coal seams.

Conclusion

The development of hydraulic punching technology has made phased progress so far, and it plays a more and more important role in the field of pressure relief and permeability increase of coal seams. The sustainable development of this technology and the rapid follow-up of equipment will improve the ability of comprehensive gas prevention and independent innovation in coal mines in our country. Based on the rock breaking mechanism of water jet, the characteristics and shortcomings of different rock breaking theories are discussed in this paper. then, the research status of hydraulic punching technology in China is summarized from the point of view of different process parameters affecting punching effect and practical application of hydraulic punching site, and it is considered that the future hydraulic punching technology will continue to deepen the theoretical research of interdisciplinary, towards the integration and intelligence of punching equipment. The development of the combination of antireflection measures.

Acknowledgment

I would like to give my heartfelt thanks to my teacher, for his kindness, illuminating guidance and profound knowledge.

References

[1]. Yuan Liang. Strategic thinking on co-mining of deep coal and gas in China [J]. Journal of Coal Industry,2016,41(01):1-6.

[2]. Qin Yong, Shen Jian, Wang Baowen, etc. Deep coalbed methane accumulation effect and its coupling relationship [J]. Petroleum journal,2012,33(01):48-54.
[3]. Lu Yiyu, Huangshan, GE Zhaolong, etc. Progress and strategic thinking of pressure relief and antireflection technology of coal mine water jet in China [J]. Journal of Coal Industry,2024,47(09):3189-3211.
[4]. Zhang Jianmin, Li Quansheng, Zhang Yong, etc. Definition of deep coal mining and mining response analysis [J]. Journal of Coal Industry,2019,44(05):1314-1325.
[5]. Yuan Liang. Research progress of deep mining response and disaster prevention and control [J]. Journal of Coal Industry,2021,46(03):716-725.
[6]. he Manchao. Research progress of deep well construction mechanics [J]. Journal of Coal Industry,2021,46(03):726-746.
[7]. Wang Enyuan, Zhang Guorui, Zhang Chaolin, etc. Research progress and prospect of coal and gas outburst prevention theory and technology in China [J]. Journal of Coal Industry,2022,47(01):297-322.
[8]. Zhang Chaolin, Wang Enyuan, Wang Yibo, etc. Temporal and spatial distribution and prevention and control suggestions of coal and gas outburst accidents in China in recent 20 years [J]. Coalfield geology and exploration2021,49(04):134-141.
[9]. Liang Weiguo, he Wei, Yan Jiwei. Mechanical properties weakening and fracture mechanism of coal and rock caused by supercritical CO_2 [J]. Journal of Coal Industry,2022,47(07):2557-2568.
[10]. Men Xiangyong, Han Zheng, Gong Houjian, etc. Challenges and opportunities for coalbed methane exploration and development in China under the new situation [J]. Natural gas industry,2018,38(09):10-16.
[11]. Li Xiangfang, Pu Yunchao, Sun Changyu, etc. Recognition of the theory of adsorption / desorption of coalbed methane and shale gas [J]. Petroleum journal,2014,35(06):1113-1129.
[12]. Wang Enyuan, Wang Hao, Liu Xiaofei, etc. Spatio-temporal evolution law of coal stress and gas around hydraulic punching hole [J]. Coal science and technology,2020,48(01):39-45.
[13]. Cheng Xiaoqing, Wang Zhaofeng. Effect of coal discharge by hydraulic punching on antipermeable effect [J]. Coal mine safety,2018,49(04):148-151.
[14]. Wang Kai, Li Bo, Wei Jianping, etc. Gas permeability change law of coal seam around hydraulic punching hole [J]. Journal of Mining and Safety Engineering,2013,30(05):778-784.
[15]. Xue Fei. Study on permeability increasing mechanism and application of hydraulic punching coal seam [D]. China University of Mining and Technology (Beijing),2018.
[16]. Shen Huajian. Structure optimization and test of slotting nozzle in coal seam [J]. Coal mine safety,2020,51(04):10-13.
[17]. Lu Yiyu, Jia Yajie, GE Zhaolong, etc. Fluid-solid coupling model of coal seam gas after slotting and its application [J]. Journal of China University of Mining and Technology,2014,43(01):23-29.
[18]. Yan Fazhi, Zhu Chuanjie, Guo Chang, etc. Numerical simulation and test of antireflective technical parameters of slotting and fracturing [J]. Journal of Coal Industry,2015,40(04):823-829.
[19]. Wang Jie, Lin Baiquan, Ru Apeng. Numerical experiment on the process of slotted gas discharge from low permeability coal seam [J]. Coal mine safety,2005(08):4-7.
[20]. Yuan Liang, Lin Baiquan, Yang Wei. Research Progress and Development Direction of Coal Mine Hydro-technology Gas Control in China [J]. Coal science and technology,2015,43(01):45-49.
[21]. Sun Bingxing, Wang Zhaofeng, Wu Hourong. Application of hydraulic fracturing technology in gas drainage [J]. Coal science and technology,2010,38(11):78-80+119.
[22]. Lu has a factory. Application of hydraulic fracturing technology in mines with high gas and low permeability [J]. Journal of Chongqing University, 2010,33(07):102-107.
[23]. Feng Yanjun, Kang Hongpu. Fracture initiation and expansion analysis of hydraulic fracturing [J]. Journal of rock mechanics and engineering,2013,32(S2):3169-3179.
[24]. Li Dong, Lu Yiyu, Glory, etc. Fast coal uncovering technology of large cross-section gas tunnel based on directional hydraulic fracturing [J]. Rock and soil mechanics,2019,40(01):363-369+378.

[25]. Lu Yiyu, Li Rui, Xian Xuefu, etc. Discussion on efficient development of deep coalbed methane by surface directional well + hydraulic slotting pressure relief method [J]. Journal of Coal Industry,2021,46(03):876-884.
[26]. Liu Yong, he an, Wei Jianping, etc. Water jet pressure relief and anti-penetration plugging inducement and a new method of plugging removal [J]. Journal of Coal Industry.2016,41(08):1963-1967.
[27]. Rozantsev E S, Vershinin N G, Rudakov V A. Properties of burst-prone Kuzbass seams as a criterion for assessing the applicability of hydraulic flushing of cavities[J]. Soviet mining science, 1969, 5(2): 179-182.
[28]. Ren Peiliang. Research and application of hydraulic punching pressure relief and permeability increasing technology [D]. Jiaozuo: Henan University of Technology，2009.
[29]. Yu Qixiang. Technology of coal roadway driving to prevent coal and gas outburst-advanced hydraulic punching [J]. Journal of Beijing Institute of Mining Technology,1959(04):54-59.
[30]. Han Ying, Dong Bowen, Zhang Feiyan, etc. Research progress of hydraulic punching pressure relief and permeability increasing technology in China [J]. China's mining industry,2021,30(02):95-100.
[31]. Lu Yiyu, Huangshan, GE Zhaolong, etc. Progress and strategic thinking of pressure relief and antireflection technology of coal mine water jet in China [J]. Journal of Coal Industry,2022,47(09).
[32]. Wang Ruihe, Ni Hongjian. Study on rock breaking mechanism of high pressure water jet [J]. Journal of University of Petroleum (Natural Science Edition) ,2002(04):118-122+0.
[33]. Xu Xiaohe, Yu Jing. Rock fragmentation [M]. Beijing: coal Industry Press,1984.
[34]. Guo Jun. Study and application of anti-permeability mechanism of high-pressure hydraulic cutting in soft coal seam with low permeability [D]. Beijing University of Science and Technology,2019.
[35]. Cao S, Ge Z, Zhang D, et al. An experimental study of ultra-high pressure water jet-induced fracture mechanisms and pore size evolution in reservoir rocks[J]. International Journal of Rock Mechanics and Mining Sciences, 2022, 150: 104995.
[36]. Liao Hualin, Li Gensheng, Yi can. Research progress of rock fragmentation theory under the action of water jet [J]. Metal mine,2005(07):1-5+66.
[37]. Liao Hualin, Li Gensheng, Niu Jilei. Analysis of influencing factors and mechanism of rock breaking by ultra-high pressure water jet under submerged condition [J]. Journal of rock mechanics and engineering,2008,(06):
[38]. Zhou Q, Li N, Chen X, et al. Analysis of water drop erosion on turbine blades based on a nonlinear liquid–solid impact model[J]. International Journal of Impact Engineering, 2009, 36(9): 1156-1171.
[39]. Wang Ruihe, Ni Hongjian. Theoretical study on drilling process of rock breaking by high pressure water jet [J]. Journal of University of Petroleum (Natural Science Edition) ,2003,(04).
[40]. Bowden F P, Brunton J H. The deformation of solids by liquid impact at supersonic speeds[J]. Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences, 1961, 263(1315): 433-450.
[41]. Ge Z, Zhang D, Lu Y, et al. Propagation of stress wave and fragmentation characteristics of gangue-containing coal subjected to water jets[J]. Journal of Natural Gas Science and Engineering, 2021, 95: 104137.
[42]. Liu Mingju, Ren Peiliang, Liu Yanwei, etc. Theoretical analysis of coal breaking of hydraulic punching anti-outburst measures [J]. Journal of Henan University of Technology (Natural Science Edition) ,2009,28(02).
[43]. look to the north. Study and application of damage evolution law of slotted coal with high pressure water jet [D]. China University of Mining and Technology (Beijing),2016.
[44]. Farmer I W, Attewell P B. Rock penetration by high velocity water jet: A review of the general problem and an experimental study[C]//International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts. Pergamon, 1965, 2(2): 135-153.
[45]. GE Zhaolong, Lu Yiyu, Zhou Dongping, etc. Study on the law and mechanism of gas desorption experiment promoted by acoustic shock effect of cavitation water jet [J]. Journal of Coal Industry,2011,36(07):

[46]. Lu Yiyu, Feng Xinyan, Li Xiaohong, etc. Experimental analysis of rock crushing by high pressure cavitation water jet [J]. Journal of Chongqing University (Natural Science Edition) ,2006,(05):

[47]. Xiang Wenying, Li Xiaohong, Lu Yiyu, etc. Experimental study on the effect of cavitation jet [J]. Mechanical engineering in China,2006,(13):

[48]. Lu Yiyu, Li Xiaohong, Yang Lin. Theory of bubble collapse in pulsed abrasive jet [J]. Journal of Chongqing University (Natural Science Edition) ,2003,(05):

[49]. Lu Yiyu, GE Zhaolong, Li Xiaohong, etc. Numerical analysis of cavitation development and collapse process [J]. Journal of China University of Mining and Technology,2009,38(04):

[50]. Crow S C, Champagne F H. Orderly structure in jet turbulence[J]. Journal of fluid mechanics, 1971, 48(3): 547-591.

[51]. Jiabao Z,Dingqi L. Research on Optimization of Large Flow Hydraulic Punching Process in Zhaozhuang Mine[J]. Geofluids,2022,2022.

[52]. Xie, S., et al., Numerical simulation study on gas drainage by interval hydraulic flushing in coal seam working face. Energy Exploration & Exploitation, 2021. 39(4): p. 1123-1142

[53]. Yang Tenglong, Meng Rui. Study on anti-penetration effect of hydraulic punching in downward drilling [J]. Coal engineering2022,54(S1):62-66.

[54]. Ma Heng, Gong Zheng, Hi-Tech, etc. Optimization of high pressure air jet parameters and analysis of erosion characteristics of similar coal materials [J]. Coal mine safety,2023,54(10):8-15.

[55]. Lu Yiyu, Zhu Zhidan, Tang Jiren, etc. Study on the performance of crushing hard rock with pressurized pulsed water jet [J]. Vibration and shock,2023,42(07):114-122.

[56]. Min R, Chen X, Wang L, et al. Study and application of reasonable parameters for hydraulic punching of layer penetration boreholes in Changping Coal Mine[J]. Energy Science & Engineering, 2023, 11(9): 3020-3032.

[57]. Chen Shuliang, Huang Bingxiang, Xu Jie, etc. Experimental study on the basic law of high pressure water jet punching [J]. Coal mining,2017,22(04):1-3+38.

[58]. Wang Feng, Tao Yunqi, Liu Dong, etc. Experimental study on the influence of drilling angle on hydraulic punching effect [J]. Coal mine safety,2018,49(04):1-4.

[59]. Zhao Jiangnan, Lei Zeyong, Zhong Lin, etc. Research progress of high pressure water jet nozzles [J]. Clean the world. ,2023,39(01):45-48.

[60]. Chai Xijun, Yang Chengtao, Xiong Junjie. Study on the design of hydraulic punching nozzle in coal seam [J]. Coal mine machinery,2022,43(11):15-17.

[61]. Rose, W.G., A swirling round turbulent jet,1-Mean-flow measurements, J. of Appl.Mech,vol.Dec.,1962:615-625.

[62]. Raju, S.P., Ramulu, M., Predicting hydro-abrasive erosive wear dining abrasive waterjet cutting - part 2: an experimental study and model verification. PED-Vo.l,1994,,68-1:381-396.

[63]. Chigier,N.A.,and Chervinsky A.,Experimental investigations of swirling vortex motion in jets,J.ofAppl. Mech.,vol.34,1967:443-451.

[64]. Farokhi,S.,Taghavi R.and Rice,E.J.,Effects of initial swirl distribution on the evolution of a turbulent jet,AIAA Journal, Vo.127(6),1989:700-706.

[65]. Tao Yunqi, Feng Dan, Ma Geng, etc. Study on physical simulation test of hydraulic punching and its pressure relief and permeability increasing effect [J]. Coal science and technology,2017,45(06):55-60.

[66]. Wang Qingguo, Si Junting, Liu Yang, etc. Research and application of hydraulic punching technology in Hongyang No.2 Coal Mine. Energy and environmental protection, 2018. 40(8).

[67]. Liu Ting, Lin Baiquan, Zhao Yang, et al. Precision punching technology and application of gas non-equilibrium coal seam [J] . Coal Science & Technology (0253-2336), 2023, 51(2).

[68]. Ren Peiliang, Liu Yanwei, Han Hongkai, etc. Study on the influence of coal scouring rate on pressure relief and permeability increase and gas drainage in coal seam [J]. Coal science and technology,2022,50(10):102-109.

[69]. Hui Yubo, Zheng Yujing, Zhao Longgang, etc. Study on the influence of hydraulic punching on coal slope deformation of mining roadway in soft coal seam [J]. Coal technology,2023,42(02):39-43.

[70]. Tao Yunqi, Zhou Zhengtao, Xu Dongdong. Application of punching and pressure relief extraction technology in outburst coal seam of Zhongmacun Coal Mine. Coal mine safety, 2018. 49(4):
[71]. Wei Jianping, Li Bo, Liu Mingju, etc. Determination of effective influence radius of hydraulic punching and optimization of drilling parameters [J]. Coal science and technology,2010,38(05):39-42.
[72]. Zhang Mingjie, Li Yaxi, Yan Jiangwei, etc. Gas emission attenuation characteristic method is used to determine the influence radius of hydraulic punching extraction [J]. Coal science and technology,2022,50(07):156-162.
[73]. He Jun, Hao Yunfei. Study on effective influence radius of hydraulic punching under space-time effect [J]. Coal technology,2023,42(05):112-116.
[74]. Liu Yong, Liu Jianlei, Wen Zhihui, etc. Study on gas drainage technology of multi-stage coal-breaking hydraulic punching to strengthen soft and low permeability coal seam [J]. Science and technology of production safety in China,2015,11(04):27-32.
[75]. Wang Zhaofeng, Fan Yingchun, Li Shisheng. Application of hydraulic punching technology in soft and low permeability outburst coal seam [J]. Coal science and technology,2012,40(02):52-55.
[76]. Liu Yingzhen, Liu Yanwei, Hao Tianxuan. Research and application of hydraulic punching cover coal roadway driving technology [J]. Coal science and technology2013,41(11):82-85.
[77]. Liu Yanwei, Ren Peiliang, Xia Shibai, etc. Investigation and analysis of pressure relief and permeability enhancement effect of hydraulic punching measures [J]. Journal of Henan University of Technology (Natural Science Edition) ,2009,28(06):695-699.
[78]. Tan Dongsheng, Zhang Shijie, Yanlin. Study on pressure relief and penetration enhancement effect of hydraulic punching and hydraulic cutting in soft coal seam [J]. Shandong coal science and technology,2021,39(05)
[79]. Xu Dongfang, Huang Yuanyue, Luo Zhishun, etc. Research and application of hydraulic punching pressure relief and permeability increasing technology in floor roadway [J]. Coal science and technology,2013,41(02)
[80]. Li Lei, Zhou Shaoxi. Analysis and evaluation of permeability enhancement effect of hydraulic punching in "three soft" low permeability coal seam [J]. Coal technology,2021,40(09)
[81]. Shao Guojie. Design of hydraulic punch while drilling [J]. Coal mine machinery,2019,40(12)
[82]. Wang Zhijian, Gui Hongwei. Integrated anti-penetration technology of drilling and expanding through outburst coal seam [J]. Coal mine safety,2016,47(09).
[83]. Wang Jinshang, Tao Yunqi, Meng Jie, etc. Research and application of integrated pressure relief and extraction technology of drilling and percussion in low permeability and high gas seam [J]. Coal technology,2014,33(06).
[84]. Wang Shikui. Study on hydraulic fracturing anti-permeability technology of soft coal penetrating boreholes in western Henan structure [D]. Henan University of Technology,2014.
[85]. Feng Anxiang, Shi Wenbao. Research and application of anti-permeability technology of hydraulic repeated fracturing in cross-layer drilling [J]. Coal engineering,2019,51(09).
[86]. Liu Xiao. Gas drainage technology of hydraulic pressure and permeability increase in single low permeability coal seam [J]. Coal mine safety,2014,45(05).
[87]. Xu Tao, Feng Wenjun, Su Xianbo. Experimental study on enhanced extraction technology of hydraulic pressure flushing and anti-penetration in coal mine [J]. Journal of Xi'an University of Science and Technology,2015,35(03)
[88]. Xu Shengming, Wang Jianwei. Field experimental study on multiple hydraulic pressure relief and permeability increasing technology in outburst coal seam [J]. Safety and environmental engineering,2014,21(03)
[89]. Li Guanliang. Study and application of coupling penetration enhancement and gas drainage by hydraulic punching and deep-hole presplitting blasting [J]. Energy and environmental protection,2019,41(09)
[90]. Zhang Kaijia. Combined technology of hydraulic punching and carbon dioxide blasting in soft coal seam [J]. Coal engineering,2018,50(07).