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REVIEW ARTICLE

Research progress on the protection and utilization technology of water resources for coal mining in China

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ABSTRACT

Water shortage is a global problem, and China is one of the most water-scarce countries in the world. The reverse distribution of coal resources and water resources has made the protection and utilization of water resources for coal mining in China a major technical problem for the green development of coal. Western China has become the main coal-producing area, but the ecological environment in the region is fragile, the evaporation of water resources is large, and the evaporation loss after mine water discharge is the main reason for the current annual loss of 6 billion tons of mine water in coal mining in China. The technical progress and engineering application characteristics of the protection and utilization of water resources in coal mining are systematically analyzed. After nearly 20 years of technical exploration and engineering practice, Shenhua Group broke through the traditional concept, put forward the technical concept of mine water storage in the goaf for the first time, overcome the technical problems such as water source prediction, reservoir site selection, reservoir capacity calculation, dam construction, safety control and water quality assurance, and built a technical system for underground coal mine reservoirs. This technology has been fully implemented in the Shendong mining area, and will be promoted and applied in other mining areas in the western region, opening up an effective technical way for the protection and utilization of coal mining water resources.

Keywords: Coal Mining; Conservation and Utilization of Water Resources; Mine Water Storage in Goafs; Underground Coal Reservoirs

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1. Raise of questions

China is the world's largest producer and consumer of coal, and respectively accounted for 46.9% and 50.6% of the global coal production and consumption[1]. Coal accounts for 70% of China's primary energy production and consumption for a long time (**Figure 1**), coal will remain dominant in China's main energy for a long time, safety and green has become the theme of current coal mining. At present, China's coal safety situation is getting better, and the coal mortality of one million tons of coal has decreased from 5.77 in 2000 to 0.257 in 2014 (**Figure 2**). China's coal mining efficiency has reached the world's advanced level, and it is leading the world in coal machinery equipment and coal mining technology. More than 95% of the world's 10 million tons of mines are located in China.

Green mining is the core content of coal scientific development, and the protection and utilization of water resources for coal mining is a major problem facing green coal mining. The level of green coal mining in China has been slowly improved, which has seriously affected the

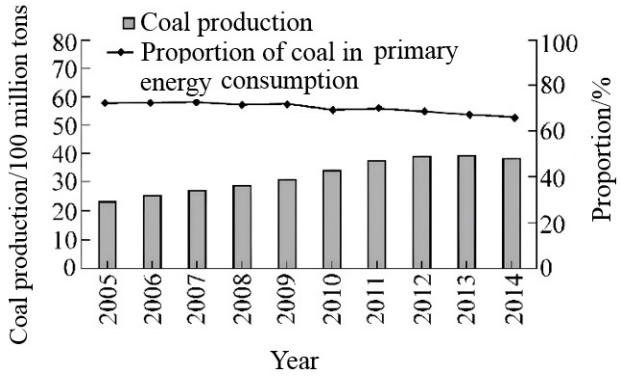

Figure 1. Production of coal and its percentage with primary energy consumption in China.

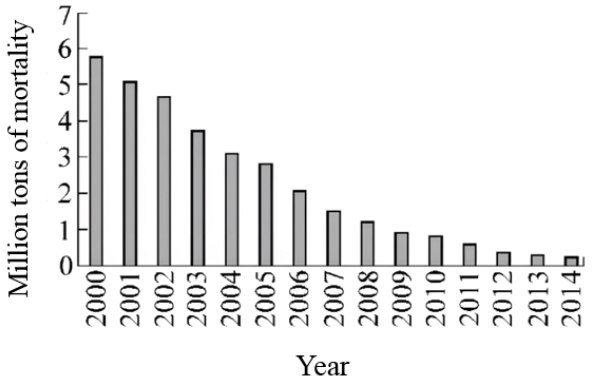

Figure 2. Million tons death rate of coal mine in 2000–2014.

improvement of the overall technical level of coal mining. Therefore, General Secretary Xi Jinping pointed out in his speech on the energy revolution on June 13, 2014 that the damage of coal mining to groundwater resources and surface ecology is the main problem facing coal development.

In view of the global problem of water shortage, the author analyzes the reverse distribution characteristics of coal resources and water resources in China; summarizes the technological progress in the protection and utilization of water resources for coal mining in western China, and points out that the storage and use of water in mines is the main technical direction for the protection and utilization of water resources in coal mining.

2. Water scarcity is a global problem

Water is the source of life, the key to production, and the foundation of ecology. According to statistics, the total reserves of water on earth are about 1.26×10^{18} m^3, sea and other saltwater account for 97.47%, freshwater accounts for only 2.53%. Among them, the total amount of freshwater resources such as river water, freshwater lake water and shallow groundwater that can be truly available to human beings is about 4.15×10^{15} m^3, accounting for only about 0.3%[2,4]. As the world's population increases, the demand for fresh water increases year by year, while the total amount of freshwater available is reduced at the speed of 6.4×10^{10} m^3/a. Currently, about 7,800 million people have limited access to available clean freshwater resources, and more than 2 billion people live in areas with high water supply constraints. By 2050, 67% of the world's population is expected to live in areas where water resources are severely scarce[5,10].

China's water scarcity began in the 1970s; since the 1980s, China's water shortage has gradually spread from local to the whole country, which has had a serious impact on the national economy. China is one of the most water-scarce countries in the world, and in 2014, the per capita water resources were less than 2,000 m^3, and the water resources situation was extremely severe[11]. The distribution of freshwater resources in China is uneven, which is manifested as "more in the south and less in the north, more in the east and less in the west". Yangtze River Basin and the area south of it account for 36.5% of the country, and water resources account for 81% of the country's water resources; Huai River Basin and its north accounts for 63.5% of the national areas, while accounts for only 19% of the country's water resources. The population in the north of China accounts for 2/5 of the total population of the country, but the water resources account for less than 1/5 of the total water resources in the country[12-14]. In terms of water volume, more than 400 of the 561 cities above the prefecture level in the country are short of water. In order to alleviate the shortage of regional water resources, China has successively built a number of large-scale cross-basin water transfer projects, such as the South-to-North Water Diversion Project, Luan River–Tianjin Water division Project, the Water Diversion Project from Yellow River to Qingdao in Shandong, the Shanxi Wanjiazhai Yellow River Diversion Project, and Han-to-Wei River Diversion Project[15], which have partially alleviated the problem of regional water shortage.

3. The protection and utilization of water resources is a major technical problem facing the green development of coal

3.1 Reverse distribution of coal resources and water resources in China

Relevant studies of the Chinese Academy of Engineering have shown that China's coal-bearing basins and coal resources show a "#"-shaped distribution pattern, that is, coal resources are controlled by the east-west spreading Tianshan–Yinshan tectonic belt, the Kunlun–Qinling–Dabie Mountain tectonic belt, and the south–north spreading Daxing'anling–Taihang Mountain–Xuefengshan tectonic belt, and the Helan Mountain–Liupan shan–Longmen Shan tectonic belt. The distribution of coal resources has the characteristics of more in the west and less in the east, more in the north than in the south, and deep in the east and shallow in the west[16]. At present, the mining depth of old mining areas such as Xinwen and Xuzhou in the east has reached about 1,000 m, the resources are increasingly depleted, and the mining complexity is increasing. The western region has become a major coal-producing area with shallow coal burial, thick coal seam and relatively simple mining conditions, accounting for 70% of the country's coal production and the proportion is continuously increasing (**Figure 3**).

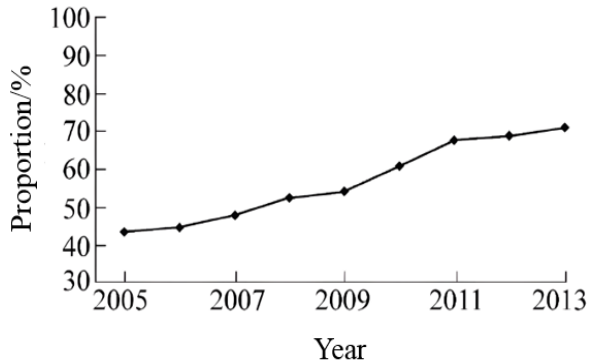

Figure 3. The proportion of coal production in the western region as a proportion of the country.

China's water resources and coal resources show a reverse distribution, and most of the coal-rich areas in the central and western regions are in arid and semi-arid ecologically fragile areas, with water shortages and fragile surface ecology. Water resources of major coal bases are in short supply, and water supply in mining areas mainly depends on the extraction of groundwater resources and comprehensive utilization of mine water. The construction of mining areas is facing difficult problems of water searching, comprehensive utilization of water resources and allocation of water rights[17].

3.2 The protection and utilization of water resources is a major problem facing the development of coal in the western region

The protection and utilization of water resources is a long-term challenge for coal development. According to statistics, China mined 1 tons of coal produces about 2 tons of mine water, but the utilization rate of mine water is only about 25%[18-20]. At present, the annual production of mine water is about 8 billion tons[21], and the annual loss of mine water is 6 billion tons, which is equivalent to 60% of China's annual industrial and civil water shortage (10 billion tons). The main reason for the loss of water resources in coal development is that the mine water discharged on the surface is not effectively utilized, especially in the western mining area.

The climate in the main coal-producing areas in western China is arid, and the annual evaporation is more than 6 times that of precipitation, so in order to ensure safe production, the mine water is discharged from the surface, but due to the large amount of evaporation, it cannot be effectively stored and used. How to achieve mutual coordination between coal development and water resources protection and utilization is a major technical problem facing the green development of coal in the western mining area, and it is also one of the core contents of the construction of ecological civilization in the western mining area.

3.3 The state attaches great importance to the protection and utilization of mine water

The protection and utilization of mine water has become a difficult point and hot issue in the green development of coal, which has attracted the attention of the whole society. General Secretary Xi Jinping pointed out at the sixth meeting of the

Central Leading Group for Finance and Economics: China's coal resources are abundant, and the status of the "coal boss" as the main energy source of our country will not change for a long time. The large-scale mining and use of coal brought about two major problems: first, the destruction of groundwater resources and surface ecology by coal mining; the second is the damage to the environment caused by coal consumption.

In order to solve the above-mentioned difficult problems, the party and the state have promulgated a series of policies and regulations for the protection and utilization of coal development and water resources, and put forward strict requirements. In May 2015, the CPC Central Committee and the State Council pointed out in the *Opinions on Accelerating the Construction of Ecological Civilization* that "actively develop and utilize unconventional water sources such as regenerated water, mine water, aerial cloud water, and seawater, strictly control disorderly water transfer and artificial water feature projects, and improve the safety and security of water resources". In April 2015, the State Council pointed out in the *Action Plan for the Prevention and Control of Water Pollution* (Water Ten Articles) that "to promote the comprehensive utilization of mine water, the supplementary water use of coal mining areas, the production and ecological water of surrounding areas should give priority to the use of mine water, and strengthen the recycling of coal preparation wastewater". In April 2015, the National Energy Administration's *Action Plan for Clean and Efficient Utilization of Coal (2015–2020)* proposed to "increase the utilization of coal gangue, slime, coal mine gas, mine water and other resources", "mining areas with suitable conditionals need to implement water conservation and mining or coal-water co-mining, to achieve the integration of mine water inrush control and water resource protection". In January 2015, the National Energy Administration and others pointed out in the *Opinions on Promoting Safe and Green Development and Clean and Efficient Utilization of Coal* that "coordinate coal resource conditions, mine geological environment, water resource carrying capacity and ecological environment capacity, and determine reasonable scientific production capacity", using water resources as a constraint on coal scientific production capacity. *The Environmental Protection Law of the People's Republic of China*, revised by the National People's Congress in 2015, for the first time enshrined "safeguarding public health" in Article 1 of the General Provisions and explicitly stipulated the principle of "giving priority to protection. In June 2014, the State Council's *Strategic Action Plan for Energy Development (2014–2020)*" stipulated that "according to the characteristics of regional water resource distribution and the carrying capacity of the ecological environment, strict environmental protection and safety access standards for coal mines, and promote green mining technologies such as filling and water conservation". In March 2012, the National Development and Reform Commission also put forward clear indicators and requirements for mine water utilization and surface ecological restoration in the *Twelfth Five-Year Plan for the Development of Coal Industry*. In February 2012, the State Council proposed in the *Opinions of the State Council on the Implementation of the Strictest Water Resources Management System* (State issued [2012] No. 3) to establish a red line for the control of water resources development and utilization, identified specific indicators and requirements, and clearly pointed out that the construction of major projects should be adapted to local water resources conditions[22-29]. The communiqué of the Fifth Plenary Session of the Eighteenth Central Committee of the Communist Party of China put forward the five development concepts of innovation, coordination, greenness, openness, and sharing, once again emphasized the basic national policy of conserving resources and protecting the environment, and raised the "quality of the ecological environment" to a new height.

The above-mentioned policies and regulations have put forward more stringent requirements for the protection and utilization of mine water, especially in the main coal-producing areas in the western region, it is necessary to develop technologies that are corresponding to each other, so as to achieve the coordinated development of coal mining and water resources protection and

utilization.

4. Technological progress in the protection and utilization of water resources in coal mining

For a long time, in view of the impact of coal mining on groundwater, a large number of technical research and engineering practices have been carried out at home and abroad. Academician Qian Minggao took the lead in proposing the concept of green coal mining and several areas of research on water conservation and mining technology in western mining areas, pointing out that it is necessary to develop technologies suitable for coal mining and water resources coordination in western mining areas[30,32]. Accordingly, different institutions and scholars have carried out a large number of research work, including basic research on the "three belts" of coal mining and the law of groundwater movement of coal mining[33-40], forming two types of technical approaches: first, water retention mining technology characterized by the "interception method"; the second is the mine water storage and utilization technology characterized by the "diversion method."

4.1 Water-retaining mining technology characterized by the "interception method"

The core of the "interception method" of water retention mining technology is to protect the integrity of the aquifer above the coal seam and avoid the formation of water diversion fractures, thereby blocking the downward seepage of underground water and achieving the purpose of protecting the groundwater of the aquifer. The main technical means used include fill mining, height limit mining, house-pillar mining, and water retention area division[41-47].

Filling mining has been well applied in the eastern and central mining areas of our country, especially in the coal mining "three underground areas" (buildings, railways and water bodies), but to promote its application in the main coal-producing areas in western China, it is necessary to solve the problems of improving the efficiency of filling and reducing the cost of filling. In view of the protection of groundwater for coal mining in western China, relevant scholars have developed technologies such as water retention area division, pillar mining and strip mining based on ecological water level protection[48-50], but their promotion and application still need to solve the problems of improving the extraction rate of coal resources.

4.2 Mine water underground storage technology characterized by "diversion method"

The technology is to use the means of diversion, on the basis of mastering and using the law of groundwater transportation and migration of coal to extract groundwater, transfer mine water to the goaf area for storage, and build corresponding extraction and utilization projects to ensure that mine water does not drain out of the surface, and realize the protection and utilization of mine water resources.

After nearly 20 years of technical research and engineering practice in the Shendong mining area, Shenhua Group has successfully developed the coal mine underground reservoir technology, that is, using the goaf hollow space gap formed by coal mining, connecting artificial dam body to unconnected safety coal pillars to form a reservoir dam body to form a relatively closed water storage space, while constructing mine water injection facilities and water intake facilities, making full use of the goaf area rock mass on the natural purification of mine water, to achieve mine water storage and utilization[51,52], the technology has been successfully fully implemented in Shendong mining area.

4.3 Technological exploration of the protection and utilization of groundwater resources for coal mining

In view of the problem of water drainage losses from coal mining wells in the western mining area, Shenhua Group, together with China University of Mining and Technology (Beijing), China University of Mining and Technology, Tsinghua University, Xi'an Research Institute of China Coal Science and Industry Group, and other universities and scientific research institutions, has carried out a number of scientific and technological innovation projects and engineering practices in the

Shendong mining area, such as *Technology for Protective Mining and Comprehensive Utilization of Water Resources in Shendong Mining Area*, *Research and Application of Protective Coal Mining Technology for Water Resources in Shendong Mining Area*, and *Research on the Law of Modern Coal Mining on Groundwater Resources and Ecological Impact in Shendong Mining Area*. We have mastered the law of transport and movement of coal mining groundwater in the Shendong mining area, and carried out technical explorations for the protection and utilization of mine water: first, we have tried to prevent the generation of mine water, mainly using height limiting and filling mining techniques; the second is to build water storage facilities on the ground; the third is to explore the storage of mine water underground.

Studies have shown that although it is technically feasible to implement filling mining and height limiting of mining in the Shendong mining area, it is difficult to implement it on a large scale for the efficiency of coal mining and the rate of coal resource extraction are significantly reduced. The construction of water storage facilities on the ground is also unable to implement because of technical problems such as difficulties in land acquisition, evaporation and waste of water resources, and serious pollution of water bodies. Accordingly, Shenhua Group broke the traditional concept, carried out the technical exploration of mine water storage in the underground goaf area, experienced the technical development process of goaf water storage facilities, coal mine underground reservoirs and coal mine distributed multi-layer underground reservoirs, and built a relatively complete technical system of coal mine underground reservoirs, including water source prediction, reservoir site selection, reservoir capacity design, dam construction, safety monitoring and water quality control[53,54].

5. Coal mine underground reservoir technology has been successfully applied in western mining areas

Shenhua Group has successfully applied coal mine underground reservoir technology in Shendong mining area, and has built a total of 35 coal mine underground reservoirs with a water storage capacity of about 25 million m^3. In addition, the first coal mine distribution multi-layer underground reservoir was built in the Daliuta Mine of Shendong Mining Area, consisting of 3 underground reservoirs in Coal Seam 2 and 1 underground reservoir in Coal Seam 5, with a storage capacity of 7.1 million m^3, realizing no discharge of water from the mine. In the past three years, the underground reservoir of the coal mine has supplied more than 95% of the water used in the mining area, and in 2014, the water supply of the coal mine underground reservoir reached 65 million m^3, providing water resources for the world's only 200 million ton-class mining area, creating economic benefits for Shendong mining area 27.85 billion yuan in three years, including the savings of domestic and production water purchase 23.29 billion yuan and savings of mine water discharge costs, surface water treatment costs and sewage costs, etc., 4.56 billion yuan.

Shenhua Group has mastered the complete set of independent intellectual property rights of this technology, and has declared more than 70 domestic patents in coal mine underground reservoirs: of which 51 patents have been authorized (29 invention patents). The application of 4 PCT patents has opened up a new path for the protection and utilization of coal mining water resources in the main coal-producing areas in western China, and has realized the coordination between coal mining and water resources protection and utilization. Among them: the invention patent of "a distributed utilization method of underground water in mines" won the 17th China Patent Gold Award, becoming the third Chinese patent gold award won by the coal industry since the establishment of the award in 1989; the achievements of "key technologies for modern groundwater mining groundwater and surface ecological protection of coal in ecologically fragile areas" supported by this technology as the core technology won the second prize of national scientific and technological progress; the achievement of "key technologies and applications of coal mine underground reservoirs" won the first

prize of scientific and technological progress in the Inner Mongolian Autonomous Region.

This technology has been successively popularized and applied by the Ministry of Land and Resources and the Ministry of Science and Technology of the State as an advanced technology throughout the country, and the World Coal Association has produced special cases of coal mine underground reservoirs to promote its application in major coal enterprises in the world. Shenhua Group has comprehensively promoted the application of this technology in its coal mining areas, including Baotou Mining Area, Xinjie Mining Area, Yushen Mining Area, Ningdong Mining Area, Dayan Mining Area, Xinjiang Mining Area, etc.. In September 2015, the Ministry of Science and Technology of the People's Republic of China approved the "state key laboratory of water resources protection and utilization of coal mining" built by Shenhua Group with coal mine underground reservoirs as the core technology, and Shenhua Group will committed to the research and development and engineering implementation of water resources protection and utilization technology in mining areas under different geological characteristics and coal mining conditions in western China, providing scientific and technological support for the protection and utilization of coal mining water resources in western China.

6. The technical development direction of underground reservoirs in coal mines

Coal mine underground reservoir technology involves mining engineering, engineering geology, hydrogeology, water conservancy engineering and environmental engineering and other disciplines, which is a complex system engineering, facing many technical problems, such as water source prediction, reservoir site selection and planning, water storage coefficient calculation, dam construction process, dam body parameter design, inter-reservoir passage construction, safety assurance technology, purification law of rock mass to mine water, water quality control, high mineral water treatment and other basic theory and application technical problems. Relying on the State Key Laboratory of "coal mining water resources protection and utilization", and uniting national and foreign scientific research institutes to form a technical system for the protection and utilization of water resources applicable to the main coal-producing areas in western China. The following research work will be carried out in the future:

(1) Evaluation of the impact of coal mining on groundwater system and theoretical study of dynamic balance of regional water resources which includes: the evolution law and control mechanism of cracks in coal mining rock masses, the influence of coal mining on groundwater system, the changes in stress field caused by coal mining and the impact of groundwater level, and the theory and technology of regional water resource dynamic balance.

(2) Research on the basic theory of underground reservoirs in coal mines which includes the "three fields" relationship and evolution mechanism of the mining stress field, the fissure field and the seepage field of coal mining; self-purification mechanism of mine water by rock mass in goaf area; the impact of water storage in underground reservoirs on groundwater circulation systems and surface vegetation growth in coal mines; coal mine underground reservoir dam body safety and water body optimization scheduling theory, etc.

(3) Research and development of key technologies for underground reservoirs in coal mines which includes the study on the construction process and parameter optimization of dam bodies in underground reservoirs in coal mines, the technology for ensuring the safety of coal mine underground reservoirs, the technology for coordinating the operation of coal mine underground reservoirs, the technology for ensuring the water quality of coal mines, the technology for grading and processing water quality in coal mines, and the technology for efficient recycling of mine water.

(4) Theories and techniques of ecological construction of mining areas based on water resources protection which includes the relationship

and mechanism of groundwater system changes and ecological environment systems, the laws of the impact of coal mining on the surface ecological environment system, the law of the impact of efficient coal development on the surface ecology, and the evaluation of the ability of coal mining to restore the ecological restoration capacity of the surface.

(5) Increase the popularization and application of coal mine underground water reservoir technology, formulate technical standards for enterprises and industries, and accelerate the promotion of this technology in the western water-scarce mining areas; It will be gradually promoted in other areas of western China where conditions are suitable, including in the open pit coal mines.

7. Conclusion

(1) Water shortage is a global problem, especially in the western mining areas of China's main coal-producing areas, due to special geographical and climatic conditions, drought and little rainfall, the contradiction between water supply and demand is very prominent, which seriously restricts the green development of coal in the region.

(2) Water retention mining technology characterized by the concept of "interception method" must further solve technical problems such as improving mining efficiency and coal resource extraction rate.

(3) Coal mine underground reservoir technology, as a representative technology of the concept of "diversion method", has realized the coordinated exploitation of coal resources and water resources, and opened up an effective technical way for the protection and utilization of groundwater for coal mining in the west.

(4) The technically complex system engineering of coal mine underground reservoirs involves mining, water conservancy, geology and environment, and other disciplines, and it is also necessary to further carry out relevant basic theoretical research and technical research, so as to form a theoretical and technical system suitable for different geological and mining conditions, and provide scientific and technological support for the protection and utilization of 6 billion t of mine water lost by coal mining in China each year.

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Conflict of interest

The authors declared no conflict of interest.

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