Review Article

Research Review of Coal Mine Water Treatment Technology

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ABSTRACT

A large amount of mine water is produced during coal mining. The treatment and reuse of mine water is a significant research topic in the environment with shortages of water resources. In this paper, the characteristics of coal mine water are systematically reviewed based on previous studies. The water quality conditions of coal mine water, the particle size of suspended particles, and the aggregation stability of particles in coal mine water were reviewed in summary. The application of Stokes law and EDLVO theory in the field of water sedimentation in coal mines is illustrated. The types of sedimentation tanks used in the settlement of coal mine water and their characteristics are also reviewed according to the treatment technology. It provides significant assistance in the selection of sedimentation tanks.

Keywords: coal mine water; water reuse; treatment technology; EDLVO theory; sedimentation tank

1. INTRODUCTION

Coal holds a highly important strategic position as the primary source of energy for economic development. During the process of mining coal, a lot of coal mine water is generated. In China, every ton of coal mined results in the generation of two to three cubic meters of wastewater[1]. Discharging coal mine wastewater directly makes a large number of water resources wasted, in addition, the toxic substances in directly discharged coal mine wastewater would damage the ecological environment.[2]Therefore, research on the treatment process of coal mine water so that the mine water can be reused has great significance.

With the continuous improvement of the technological level in the coal industry, coal mine water treatment and utilization technology have also been developed fast. Coal mine water treatment technology is being improved gradually from the earliest simple precipitation treatment to deep treatment and then to zero discharge technology. However, the utilization rate of coal mine water is still not very high. According to the results of the study, [3] the total amount of water resources in Chinese coal mines is approximately 6.89 billion cubic meters, but the average utilization rate is only 35% in 2018.

In 2012, Shi Xiaomeng et al.[4] analyzed the issues in the process of mine water treatment and utilization of Zhang Shuanglou coal mine based on the water quality and quantity. They optimized the design of the coal mine water treatment and utilization system. The process of coal mine water treatment is shown in Figure 1. And they determined the coagulant which applies to the mine area is polymeric iron sulfate.

Fig. 1. Process of coal mine water treatment

In 2013, Zhou Rulu et al.[5] designed a process system for the underground treatment of coal mine water. The system uses a combination of aeration oxidation ponds and pressure-type air-water mutual flushing filter ponds in the mining area formed after coal seam mining to handle coal mine water directly underground and then use it as water for dust control and equipment cooling. The processing system is suitable for underground coal mine tunnel environment because it doesn't need to add chemical agents, so it has the advantages like short process, few treatment facilities, low treatment cost, high automation, and stable operation. To address the problems of large infrastructure investment and high operating costs of traditional mine water treatment technologies, in 2014, Li Fuqin et al.[6] provided a comprehensive description of new coal mine water underground treatment technologies in China, including coal mine water treatment technologies in mining areas, patented technologies for coal mine water underground treatment systems, reverse osmosis technologies for high mineralization coal mine water, super magnetic separation water purification technologies, and characteristics and engineering applications of pressure-type air-water mutual flushing filter pool mine water treatment technologies. To investigate the current status and issues of coal mine water sludge treatment in Chinese coal mines, in 2015, Mao Weidong et al.[7] analyzed the coal mine water sludge treatment facilities in more than 50 coal mines in China. The results showed that most coal mines have mine water sludge treatment facilities, but the quality of sludge treatment facilities is diverse and the final utilization pathway is narrow. Based on the practice of mine water management, in 2017, Fan Longbin et al.[8] studied the engineering technology of building distributed underground reservoirs for purification and storage, irrigation use, and de-fluoridation reformation. The results show that distributed underground reservoirs have great significance for mine production water, irrigation use can reduce the treatment cost and greatly improve the overall utilization rate of coal mine water, and de-fluoridation reformation has significantly improved the water quality. In 2018, Lv Zhiguo et al[9] implemented super magnetic separation technology in the underground treatment of coal mine water, the effluent water quality of the system was above the discharge standard of pollutants in the coal industry. The direct underground treatment of coal mine water not only realized the clear water into the warehouse and local reuse, but also created good economic benefits for coal mining enterprises, and played a good role in promoting the energy saving and pollution reduction of mine water treatment. In 2019, Shao, L. N. et al[10] analyzed the water quality characteristics of coal mine water in Chinese coal mines and explored the possibility of treating coal mine water containing suspended matter, containing iron, and manganese, and with high mineralization for domestic use. In 2020, Li Xinwang et al.[11]

replaced the submerged ultrafiltration membrane with a ceramic ultrafiltration membrane in a coal mine water treatment system. The results show that ceramic ultrafiltration membranes have a strong tolerance to shocks, this feature allowed the treatment system can operate smoothly through complex working conditions. In 2021, Catarina Mansilha et al.[12] characterized the physicochemical properties and suitability of abandoned coal mine discharge water for irrigation. Samples were collected in a local surface stream, which was analyzed for major and minor ions and trace element concentrations. They concluded that coal mine water can irrigate crops after treatment prior to release into the ditch system.

The treatment of coal mine water depends on the geography, mining method, and mining conditions of the coal mine in engineering. In this paper, we would review the properties of coal mine water and the characteristics of sedimentation tanks used in coal mine water treatment.

2. PROPERTIES OF COAL MINE WATER

During the coal mining process,[13] groundwater will seep out from the surface fissures due to the coal mining seams and roadways in the mine area, and the groundwater comes into contact with the coal and rock seams, and with the influence of human activities, the quality of groundwater becomes coal mine water. The coal mine water system is a complex system with multi-phase and multi-dispersion. Multi-phase means that the coal mine water contains suspended particles of many minerals, and multi-dispersion means that the particle size distribution of coal mine water is wide, and the chemical composition of the dispersed medium solution is quite complex. [14]Coal can be divided into peat, lignite, bituminous coal, and anthracite based on coal rank; it can also be divided into mirror coal, bright coal, and silk coal based on coal rock components. Their influence on the properties of coal mine water is relatively consistent from a macroscopic point of view. The composition of the minerals in coal mine water is shown in Table 1 below.

Table 1. Mineral composition and its percentage of coal mine water

Mineral composition	Common Materials	Percentage
Clay minerals	Kaolinite, Ilmenite and Montmorillonite	Great
Oxidized minerals	Quartz	Big
Carbonate minerals	Calcite	Medium
Sulfide minerals	Pyrite	Medium
Sulfate minerals	Gypsum	Little

Coal mine water still has the basic ionic composition of ordinary water, but the ion content has a large difference. The total ion content of surface water is about 365.50 mg/L, mine water is 980.05 mg/L, shallow well water is 1245.47 mg/L, and deep well water has a total ion content of 3211.64 mg/L.[15,16]

2.1 Sinking Characteristics of Coal Mine Water

2.1.1 Influence of water quality condition on coal mine water sinking

Water quality condition has a significant impact on the sinking effect of coal sludge in it. Physical indicators of water quality conditions include temperature, color, turbidity, transparency, etc.; chemical indicators include PH value, hardness, alkalinity, various ions, general organic matter, etc.[17] The significant effect of the sinking of coal mine water is the water hardness. Water hardness even plays a determinative role for coal mine water which is difficult to sink. The ionic compositions of the three samples with difficulty-settled coal mine water were analyzed individually, the data of which are shown in the following Table 2. From the data in Table 2, it can be seen that the hardness of the difficulty-settled coal mine water is relatively low, so the difficulty-settled coal mine water is in a stable colloid-like dispersion system.[18] The reason is that the micro-fine particles have a double electric layer structure, and the negative charge on their surface makes the coal mine water in a dispersed state due to electrostatic repulsion. Therefore, the surface of micro-fine particles has uncompensated bonding energy, and polar water molecules are oriented on the bonding energy surface to form a hydration film, which leads to a reduction in contact collisions between particles. Micro-fine particles have low mass, gravity almost has no effect on them, and the influence of the thermal movement in water molecules is relatively stronger, which leads to the fine particles could float stably in water. In summary, coal mine water with low water hardness during the process of concentration and clarification tends to add chemicals that can increase the hardness of the system as a way to improve the sinking rate of coal sludge.

Table 2. Ionic composition of difficulty-settled coal mine water

	Sample 1	**Sample 2**	**Sample 3**
hardness	2.85	4.19	6.15
Na^{+}、K^{+}	522.56	424.22	28.77
Ca^{2+}	29.16	13.62	36.96
Mg^{2+}	7.01	9.90	4.24
Al^{3+}		0.61	1.35
Fe^{3+}		2.88	2.50

2.1.2 Influence of particle size of suspended particles on coal mine water sinking

The coal sludge particles are attracted by gravity and fall in coal mine water on the one hand, and the concentration of coal sludge particles tends to be homogeneous due to Brownian motion on the other hand, the smaller the coal sludge particles are, the more intense the Brownian motion is. The Brownian motion disappears when the particle size of coal slurry is larger than the timing micron. The relationship between the settling velocity of particles and particle size under free settling conditions is in accordance with Stokes Law. Stokes Law is shown in Equation 1

$$v = \frac{2r^2(\rho - \rho_0)g}{9\eta} \quad (1)$$

In Equation 1, ‘v’ is the settling velocity of the particle; ‘r’ is the radius of the particle; ‘η’ is the viscosity of the medium; ‘ρ’ is the density of the particle; ‘ρ_0’ is the density of the medium. [19]A large number of test data show that the settling velocity of coal sludge particles bigger than 0.07mm can sink naturally; the settling velocity of coal sludge particles of 0. 01 to 0.07mm is little, and they need to sink in coagulation or flocculation state; the sinking velocity of coal sludge particles smaller than 0.01mm is extremely small, and the reason of the extremely small velocity is that the rate of Brownian motion can already fight with the free sinking velocity, and the coal sludge particles are in a state of uniform dispersion and have strong kinetic stability. Therefore, fine coal sludge particles must be flocculated and sunk under rapid coalescence conditions.

2.1.3 Agglomeration stability of coal sludge particles

During the sinking of coal sludge particles, there are interactions between individual particles. The various interfacial interactions between coal particles include DLVO interactions and non-DLVO interactions based on EDLVO theory.[20] Generally, assuming that mineral particles smaller than 20μm are spherical particles, the total potential energy of inter-particle interaction can be obtained from Equation 2.

$$V_Z = V_F + V_J + V_M \qquad (2)$$

In equation 2, 'V_F' represents the van der Waals interaction energy, 'V_J' represents the electrostatic interaction energy, and 'V_M' represents the interfacial polar interaction energy. The coalescence and dispersion behavior between coal slurry particles is related to whether 'V_Z' is positive or negative.[21] When 'V_Z' is positive, the coal sludge particles repel each other so that the mineral particles in the coal mine water are in a dispersed state; when 'V_Z' is negative 0, the coal sludge particles attract each other so that the mineral particles in the coal mine water are in a cohesive state. A large number of experimental data demonstrates that as the spacing between coal sludge particles increases, the 'V_F' van der Waals interaction energy will gradually become larger, but will always be close to zero, which indicates that the van der Waals interaction energy does not play a dominant role in the interaction between particles.[22,23] The electrostatic interaction energy VJ between coal sludge particles is always positive, which is expressed as repulsive energy. The electrostatic interaction energy 'V_J' 'between coal sludge particles is always positive, which is expressed as repulsive energy. When the dosage of flocculants and other chemicals is added increases, the electrostatic interaction energy as a whole tends to decrease, it indicates that the more polymers in the solution, the weaker the surface electrical properties of the particles, and the smaller the electrostatic repulsive energy. The interfacial polar interaction energy 'V_M' between coal sludge particles is expressed as hydrophobic attraction energy, and the interfacial polar interaction energy gradually decreases from zero as the spacing between coal sludge particles increases. Meanwhile, when the added flocculant dosage increases within the range of the optimal dosage, the interfacial polar interaction energy also tends to decrease as the contact angle of particles decreases.

2.2 Experimental Analysis of Coal Mine Water Sinking

A series of sieving tests, ash tests, flocculation and sinking speed tests were conducted by the School of Mechanical and Electrical Engineering of China University of Mining and Technology using coal sludge samples from the underground water bin of the Cuijiazhai coal mine. In the sieving test, the results of the preliminary identification by sieving showed that there were almost no particles larger than 5mm in the coal sludge samples, and the particles below 0.25mm accounted for more than 97%. The sieving test was continued by diluting the coal slurry samples into 2%, 5%, and 10% concentrations, and they obtained the parameter of the particle size of the hydraulic coal slurry. In the ash test, dry coal samples were ground in an automatic grinder, and three particle sizes of coal dust were sieved by using 250 mesh, 125 mesh, and 74 mesh screens. The pulverized coal was then heated to 500-600°C to completely carbonize and maintain a constant weight, for which the ash values for each particle size were obtained. From the ash test results, it can be deduced that the coal slurry sample is low ash pulverized coal, and the recovered coal slurry can be directly blended into the large coal for electric coal use.[24] According to the sinking speed test, when the sinking time is within 10~30min, the coal slurry is slightly turbid above the stratification area and gradually clears later, but the coal slurry is divided into the upper suspension and the lower precipitation regardless of the time period. In the test of sinking coal slurry resting angle, the test data shows that when the moisture content in coal slurry exceeds 70%, no accumulation will be formed, which indicates that the sinking coal slurry has good self-mobility.

Zhang Wenjun, Liu Jiongtian et al. [25] investigated the particle retention mechanism of centrifugal filtration and dewatering process of fine-coal slurry. They concluded that in the dynamic process of fine coal slurry centrifugation, there is a necessary condition of sieve retention of the intrinsic filter media, which determines the upper limit of particle size lost to the filtrate; the pore network retention of the secondary filter media is the main effect, which determines the lower limit of recovered particles. The importance of improving the fines recovery effect should be focused on using and strengthening the retention effect of secondary filtration media, rather than deliberately reducing the screen aperture; the feed size affects the pore structure and retention effect, and as the average size increases, the retention cut size also increases accordingly; strengthening the retention effect of secondary filtration media will lead to an increase in filter layer resistance and capillary effect, the centrifugal factor should be appropriately increased to increase the filtration drive and strengthen the capillary liquid removal; and the centrifugal factor has little effect.

3. ANALYSIS OF SEDIMENTATION TANK SELECTION

Based on the results of the above analysis of coal mine water characteristics, the design of the underground coal water decontamination process is shown in Figure 2. [26]First, the coal mine water enters the pre-sink tank, in which coagulant is added to make the coarse particles in the coal water settle, and then the sludge in the pre-sink tank is discharged by using mud scraping machinery; then the coal water passes through the hydro cyclone for the removal of fine particles and enters the underground water bin. In the process of underground treatment, the selection and structural design of the pre-sedimentation tank, the flow condition in the pre-sedimentation tank when the mud scraping machinery is not working and the flow condition in the sedimentation tank when the mud scraping machinery is working have a great influence on the decontamination of coal water.

Fig. 2. Flow chart of coal mine water decontamination process

According to the motion and trajectory of coal water in the sedimentation tank, the sedimentation tank can be divided into the following four types: spoke-flow sedimentation tank, flat-flow sedimentation tank, vertical flow sedimentation tank, inclined plate sedimentation tank. The sedimentation tank body generally includes five partitions: sewage inlet area, outlet area, sedimentation area, mud storage area and buffer area.

3.1 Spoke-flow sedimentation tank

The body of a spoke flow sedimentation tank is generally round, however there are also square tank bodies. The body construction of a spoke flow sedimentation tank is larger, but it covers a relatively limited area, and it is mostly utilized for large and medium-sized sewage treatment plants. [27] The spoke-flow sedimentation tank can be classified into three types based on the inlet and output of the tank.

Mid-inlet and week-out spoke-flow sedimentation tank: The coal mine water enters the pool body from the top to the bottom of the central inlet pipe, as the name implies, and flows radially to the periphery after the baffle action. The flow rate of coal mine water is greatest at the inlet, and after entering the pool, the flow rate gradually lowers as the sedimentation process continues, and the suspended sludge sinks to the pool's bottom. The sedimentation tank with a medium intake and peripheral outflow spokes provides a bigger sedimentation area and superior impact resistance.

Peripheral inlet and outlet spoke-flow sedimentation tank: The coal mine water enters the pool body through the peripheral inlet, flows from the outside to the center of the pool, and is discharged through the drainage pipe in the center of the pool, and the flow rate increases gradually during the flow. The flow pattern of the spoke-flow sedimentation tank is not conducive to the flocculation and sedimentation of suspended matter, and the impact resistance of the tank body is not strong due to the reduction of the sedimentation area, and the sedimentation effect is not good.

Week-in and week-out spoke-flow settling tank: The coal mine water enters from the perimeter inlet, moves through the inlet drop pipe like the center of the pool, and later flows out from the perimeter outlet of the settling tank. The water flow in the center of the pool is very slow, which is conducive to the flocculation reaction, and the settling time increases, which is conducive to improving the settling efficiency of the sedimentation tank, and the settling effect is better.

3.2 Flat-flow sedimentation tank

The flat-flow sedimentation tank consists of four main parts, which are the inlet, the shell, the sludge hopper, and the outlet. The inlet of the flat-flow sedimentation tank is arranged at the front end of the sedimentation tank, which is usually constructed in a submerged manner, and the sewage enters the inside of the sedimentation tank from the inlet.[28] The upper position of the sludge hopper after the inlet of the sedimentation tank is equipped with a baffle plate, the function of the baffle plate is to block the inlet water flow, so that the inlet water flow can be distributed to the whole sedimentation tank cross-section more quickly and evenly, which can make full use of the sedimentation space of the sedimentation tank. The sludge hopper is located at the front of the settling tank below the inlet and baffle, and the function of the sludge hopper is to gather the settled sludge and return sludge, and there is a sludge discharge pipe below the sludge hopper, and the settled sludge is gathered in the sludge hopper and discharged through the discharge pipe. Generally, in order to facilitate the discharge of mud, the bottom of the stratified sedimentation tank is equipped with a certain slope, or with mud scraping machinery for mud discharge. The flat-flow sedimentation tank outlet is usually in the form of an overflow weir located at the uppermost position of the sedimentation tank. The overflow weir ensures that the water flows evenly from the equal-width section of the sedimentation tank.

The structure of the flat-flow sedimentation tank is relatively simple, the working performance is stable, the operation cost is relatively low and the sedimentation effect is relatively good, so the flat-flow sedimentation tank is widely used. However, the size of the flat-flow sedimentation tank is big, and the distance between the inlet and outlet is long, which requires a wide floor space.

3.3 Vertical-flow sedimentation tank

The vertical flow sedimentation tank is mostly round as well as square. The vertical flow sedimentation tank consists of inlet central pipe, reflector plate, sludge hopper, sedimentation tank body, outlet baffle and outlet. The inlet center pipe is located in the center of the water flow sedimentation tank, the water flow from the center pipe into the sedimentation tank from top to bottom, due to excessive flow velocity will form a strong turbulence in the sedimentation tank to affect the sedimentation effect, so the center pipe inlet flow velocity is generally controlled within 0.03m/s, the inlet flow velocity of domestic sewage is 0.5m/s to 0.7m/s.[29] The lower part of the central tube is equipped with an umbrella-shaped reflector plate, whose function is to block the incoming water flow, so that the incoming water flow can be quickly and evenly dispersed to the whole sedimentation tank, so that the sewage can rise slowly and evenly in the whole section inside the sedimentation tank. Sewage into the sedimentation tank inside with the flow rate decreases, stable suspended matter will settle into the lower part of the sedimentation tank for the sludge bucket, the lower part of the sludge bucket is equipped with a mud discharge pipe, mud discharge is generally regular and continuous mud discharge two kinds. The upper clarified liquid flows out from the overflow weir around the sedimentation tank through the upper baffle of the sedimentation tank, which is preceded by a baffle and a scum tank and followed by a water collection tank to ensure the quality of the effluent[30].

The vertical flow sedimentation tank has the advantages of high sedimentation efficiency, convenient mud discharge, simple operation and management methods, and small footprint. However, as vertical flow sedimentation tank needs to form a vertical stable water flow for sedimentation, so vertical flow sedimentation tank has the disadvantages of large depth of the tank, construction difficulties and high cost, which is suitable for small sewage treatment plants that do not treat large amounts of water.

3.4 Inclined plate sedimentation tank

The structure of the inclined plate sedimentation tank is similar to that of the general sedimentation tank. It is divided into four parts: water inlet, sedimentation area, mud collection area and water outlet. Based on the shallow pool theory, the shallower the sedimentation tank, the shorter the sedimentation time. The inclined plate sedimentation tank uses parallel plates to divide the water flow into a bundle of thin water flow, so the flow velocity between the plates of the inclined plate sedimentation tank is very low, and the Reynolds number is about 200. Based on the laminar flow principle, the wastewater has a well settled effect between the inclined tubes with a stable flow pattern in the tube and the Froude number is from 0.0001 to 0.001. The inclined plate or inclined pipe increases the effective utilization area of the sedimentation tank, and shortens the settling distance of sludge particles in the sedimentation tank, which results in higher sedimentation efficiency. But the inclined plate or inclined pipe in the sedimentation tank is quite dense, in the process of sewage treatment will produce dirt and biofilm on the side wall. [31]The dirt deposited to a certain degree will block the inclined plate or inclined pipe, which results in higher maintenance and management costs and workload.

In the inclined plate sedimentation tank, due to the installation of the inclined plate and the different ways of water intake, the relative direction of the water flow and the installation of the inclined plate can be roughly divided into three types, upward flow, downward flow, and flat flow.[32] Upward flow is also called anisotropic flow, the water flows from the lower part of the inclined plate upward along the inclined plate, the suspended matter settles in the inclined plate and moves from top to bottom along the direction of the inclined plate, the water flow is opposite to the direction of the sediment. The downward flow is also called isotropic flow, where both the water and the suspended material flow along the inclined plate from top to bottom, with the water flowing in the same direction as the sediment. Parallel flow is also called lateral flow, where the water flows horizontally or perpendicular to the inclined plate, which is only applicable to inclined plate sedimentation tanks. The inclined plate sedimentation tank is suitable for the treatment of domestic water supply or sewage sedimentation, oil separation, tail sheet concentration， and general industry with pre-sanding.

4. CONCLUSION

Coal mine water treatment technology has a complex process flow. Research for coal mine water treatment involves several disciplines and fields. The review of treatment technology research written in this paper is only one branch. The review of coal mine water characteristics and sedimentation tank characteristics in this paper is a guide to the design and selection of sedimentation tanks. It provides an essential reference for the study of coal mine water treatment for reuse. The underground coal mine water treatment technology should be customized to the geographical environment of different mines, actual underground construction conditions, and different coal mine water characteristics. The treatment structure should be selected in conjunction with the actual situation, not bound to the existing structure, and the corresponding structure can be reasonably modified based on the specific engineering conditions.

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