Study on the dust removal and temperature reduction coupling performances of magnetized water spray

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Abstract
Dust pollution and heat damage hazards are important problems affecting underground safety production. This paper is aimed at exploring the optimal magnetization conditions of magnetized water for dust removal and temperature reduction and improving the utilization rate of water. First, the surface tension, viscosity, and specific heat capacity of water under different magnetization conditions were measured experimentally. Then, the influence law of ejection pressure on spray atomization and the changes of dust removal performance before and after magnetization of water were analyzed. Based on this, the temperature reduction effect of magnetized water under different wind speeds was analyzed, and the magnetization conditions with the best coupling performance of magnetized water were obtained. Finally, a spray system was designed to control the magnetization conditions strictly. The results demonstrate that the dust removal performance is better when the magnetic field intensity is 150 mT and the magnetization time is 80 s. Under this condition, the specific heat capacity also reaches the maximum. These research results can provide a theoretical basis for the selection of dust pollution and heat damage control measures in mines.

Keywords Magnetized water · Dust removal · Temperature reduction · CFD simulation · Heat damage

Introduction
In recent years, with the rapid development of tunneling technology in mines, the depth of mining is constantly increasing. Consequently, hazards such as dust pollution and heat damage become more and more severe (Lu et al. 2017a; Ni et al. 2020; Zhang et al. 2021; Zhang et al. 2020). When the dust concentration reaches a certain level, it may cause explosion accidents (Cashdollar et al. 2007; Gao et al. 2021; Liu et al. 2019a; Zheng et al. 2009). According to the statistics, coal dust explosion accidents account for about 9% of all kinds of dust explosion accidents in the world every year, and the proportion reaches up to 35% in China (Lu et al. 2019a, Peng et al. 2019, Yuan et al. 2015, Zhao & Nie Zhao and Nie 2011). These accidents lead to serious casualties and property losses. In addition, miners who work in a high-concentration dust environment for a long time are prone to pneumoconiosis (Gao et al. 2017; Geng et al. 2014; Hua et al. 2018; Jiang et al. 2017; Lu et al. 2017b; Zhou et al. 2018). According to the statistics of the National Health Commission of China, about 20,000 cases of pneumoconiosis are reported annually in China, accounting for about 90% of the total number of reported cases of occupational diseases (Hassan et al. 2021; Liu et al. 2021; Xu et al. 2021). Pneumoconiosis, which mostly occurs in the coal mining and picking industry, the non-ferrous metal mining industry and auxiliary mining activities, is currently the most serious occupational disease in China (Guo et al. 2020; Lu et al. 2021b; Wang et al. 2021; Xu et al. 2019b). Statistics of pneumoconiosis cases in China over the recent eight years are shown in Fig. 1.

Heat damage is another problem that cannot be ignored in the mining process. Calculated according to the average geothermal gradient 0.035°C/m in China, the rock temperature
Many scholars have conducted extensive research on these two issues. With respect to dust management in mines, the commonly used dust removal technologies include the following: ventilation dust removal, coal seam water injection, foam dust removal, air curtain dust removal, and spray dust suppression (Lu et al. 2019b; Lu et al. 2019c; Ni et al. 2019; Wang et al. 2019; Wang et al. 2020; Xu et al. 2020; Xu et al. 2019c; Yu et al. 2017; Zhou et al. 2019b). Among them, the spray dust suppression technology is the most widely adopted because it is simple, economical, and efficient (Hua et al. 2020; Ma et al. 2020). Wang et al. (2017a) studied the effect of airflow from forced ventilation on the water spray field in the heading face of coal mines. Zhou et al. (2019a) investigated in detail the factors that affect the droplet formation pattern, such as injection pressure and nozzle structure, and designed a new nozzle distribution device. Fang et al. (2020) analyzed the particle size distribution of fine water mist as well as its effect on spray dust suppression and obtained different laws of water different-sized mist in their main dust capture stages. Their research findings optimized the control scheme of mine spray dust suppression to a certain extent. Peng et al. (2019) designed an air-assisted PM10 control device, found the distribution law of its fog field, and obtained its optimal spray conditions. These studies have improved the effect of spray dust suppression to varying degrees. However, pure water possesses a limited ability to wet the dust with strong hydrophobicity in mines (Ni et al. 2021; Xie et al. 2020).

Since the early 1980s, Chinese scholars have started the researches on the application of magnetized water. Magnetized water has been widely used in dust removal, scale removal, construction, agriculture, medical treatment, and other fields now. Earlier, Liu (Liu 1991), An et al. (1998), and Zhao (2008) proposed that the external magnetic field can reduce the viscosity and surface tension of water. Nie et al. (2013) and Zhao et al. (2019) researched the relevant parameters affecting the performance of magnetized water and came up with partial rules. All these researches indicate that the magnetic field can increase the activity of water molecules so that the water adsorbs easily on the dust surface. Chen et al. (2014) further performed an experimental investigation on the dust removal efficiency of magnetized water, concluding that it is 16.36% higher than that of unmagnetized water. Nie et al. (2015), Qin et al. (2017), (Liu and Gu, 2020) enhanced the wetting ability of magnetized water by adding surfactants to it, thereby improving the dust removal efficiency. However, these researches only considered the effect of magnetic field on the dust removal performance of water, without shedding light on its effect on the ease of heat damage in mines. In terms of the temperature reduction effect of magnetized water, Huang et al. (Huang and Yao 2019) studied the role of low-temperature magnetized water in dust removal and temperature reduction. Nevertheless, they did not conduct an in-depth study on the change in the cooling properties of water after magnetization.

In summary, the performance of water for dust removal or temperature reduction has been researched on separately in detail. Nevertheless, there is a lack of research on the dust removal and temperature reduction coupling performances of water, especially magnetized water. In this paper, the surface tension, viscosity, and specific heat capacity of water under different magnetic fields were experimentally measured. Furthermore, the influence law of ejection pressure on spray atomization was obtained by numerical simulation. The dust removal and temperature reduction performances of magnetized water were further analyzed. Then, the magnetization conditions for achieving the best coupling performance were obtained. Finally, a system was designed to control the magnetization conditions strictly. The research results can provide a theoretical basis for the selection of dust pollution and heat damage control measures in mines.

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Basic theory of magnetized water to reduce dust and temperature

Mechanism of water atomization

The atomization process of water includes two stages: initial fragmentation and secondary fragmentation. During atomization, after the liquid column or film is formed by the liquid ejected from the nozzle, the deformation of the liquid surface intensifies continuously, and the fluid itself fractures under the action of external aerodynamics (Niu et al. 2021), which is called initial fragmentation. Then, the aerodynamic resistance created by the continuous aerodynamic impact keeps deforming the droplet. When the internal force of the droplet cannot maintain the original shape of the droplet, further fragmentation of the small droplet occurs, which is called secondary fragmentation (Peng 2018; Xiong 2018).

In the process of secondary fragmentation, the droplet velocity at the edge of the fog field attenuates greatly, forming a low-speed injection belt. Therefore, it is necessary to analyze the low-velocity droplets in the study on spray droplet breakage. In this paper, the TAB model is selected to probe into the atomization jet. The model, which considers that the breakage of the droplet particles is caused by the constantly intensifying amplitude vibration of the droplet surface, is suitable for the atomization jet with a small Weber number and a low speed. In the model, the surface forces on droplet particles mainly include aerodynamic force, surface tension, and viscous force. The force equation of droplet particles (Yin et al. 2019) is

$$\frac{d^2 y}{dt^2} = F_a - F_o - F_\mu$$

(1)

where $F_a$, $F_o$, and $F_\mu$ are aerodynamic force, surface tension, and viscous force, respectively, N. In accordance with the Taylor analogy, the following expressions can be derived (Xiu et al. 2020):

$$F_a = \frac{C_F \rho |u-u_d|^2}{C_b \rho_d}$$

(2)

$$F_o = \frac{C_k \sigma}{\rho_d \alpha^3} y$$

(3)

$$F_\mu = \frac{C_d \mu_d d^2 y}{\rho_0 \alpha^2} \frac{dy}{dt}$$

(4)

where $C_b$, $C_F$, $C_k$, and $C_d$ are dimensionless constants; $u_d$ denotes the relative velocity between gas and droplet, m/s; $r$ denotes the droplet radius before deformation, $\mu_m$; $\rho_d$ denotes the liquid’s density, kg/m$^3$; $\sigma$ denotes the liquid’s surface tension, N/m; and $\mu_d$ denotes the liquid’s dynamic viscosity, kg/(m·s).

Mechanism of water magnetization

The aqueous solution contains many hydrogen bonds. Water molecules are connected to each other by the hydrogen bonds to form large molecular clusters (Brewer & Peltzer Brewer and Peltzer 2019). The hydrogen bond structure formed among water molecules is unstable. Affected by the movement of water molecules, the hydrogen bonds will be broken, and new hydrogen bonds will be formed (Li et al. 2020). Ultimately, the cluster structure formed among water molecules may become larger or smaller (Zhou 2019). Zhu et al. (1999) proposed that the presence of hydrogen bonds in the aqueous solution has an important influence on the surface tension, melting point, and boiling point of the solution. In this paper, the dust removal and temperature reduction performances of water are improved by means of an external magnetic field.

$$\text{(H}_2\text{O)} \ n = \text{H}_2\text{O} + (n-1) \ \text{H}_2\text{O}$$

(5)

Experimental principle and results analysis

Tap water was chosen as the experimental material. In order to eliminate the influences of impurities and water temperature, the water was placed in the beakers for 24 h before the experiment. The laboratory environment temperature was 28°C, and the water temperature was 26°C. The water was magnetized under six magnetic field intensities, i.e., 50 mT, 100 mT, 150 mT, 200 mT, 250 mT, and 300 mT for 20 s, 40 s, 60 s, 80 s, 100 s, 120 s, 180 s, 240 s, 300 s, and 360 s, respectively, before the surface tension, viscosity, and specific heat capacity of the magnetized water were measured.

Measurement of surface tension

During the spraying process, the water needs to be dispersed into droplets. When the surface tension of water is smaller, less work needs to be done to overcome the surface tension. Accordingly, the water body can be broken more easily (Nie et al. 2013). JYW-200B micro-controlled automatic surface tension meter is used in the experiment, whose manufacturer is Changzhou Sanfeng Instrument Technology Co., Ltd. The measurement principle is ring method. To be specific, a platinum ring was immersed in the water for a certain distance, and the surface tension of the liquid was obtained by measuring the maximum tension exerted during the process of pulling the ring out of the liquid level. The measurement range...
is 0–200 mN/m; the resolution is 0.01 mN/m; and the mean value of three measurements is taken. The experimental results are displayed in Fig. 3.

The observations from Fig. 3 are as follows: (1) After the water is magnetized, the surface tension decreases to varying degrees compared with unmagnetized water. (2) Under the same magnetic field intensity, the surface tension exhibits the characteristics of multi-extreme value with the increase of the magnetization time. The surface tension drops sharply when the magnetization time is in the range of 0–80 s, reaching the minimum at 80 s. Afterwards, it fluctuates slightly as the magnetization time passes by. (3) It also varies notably when the water is magnetized under different magnetic field intensities for the same time. When the magnetic field intensity is 150 mT and the magnetization time is 80 s, the surface tension reaches the minimum which is about 8.5% smaller than that of unmagnetized water.

The experimental results obtained by Ding et al. (2011) reveal that the surface tension of tap water fluctuates according to magnetization conditions. Besides, they considered that the optimal combination of magnetic field intensity and magnetization time which boasts the strongest surface tension reduction effect is 200 mT and 35 min. Zhang et al. (2020) held that the optimal combination is 800 mT and 30 min. However, their combinations both require a long magnetization time, failing to guide practical applications. In this paper, the water only needs to be magnetized for 80 s for attaining a surface tension decrease of 6.1 mN/m, which is of great significance.

**Measurement of viscosity**

The influence of viscosity on spray is mainly reflected by the droplet size distribution (Chen et al. 2014). In the experiment, the digital viscometer manufactured by Shanghai Jitai Electronic Technology Co., Ltd was employed to measure the viscosity of the water. The viscometer used a motor to rotate the rotor at a constant speed via a torque sensor. When the rotor is subjected to viscous resistance in the tested water, the force is fed back to the torque sensor and got processed. In this way, the viscosity of the tested water is measured. The results of the experiment are shown in Fig. 4.

It can be seen from Fig. 4 that (1) the viscosity of the water is reduced after magnetic treatment. (2) The viscosity of the water does not vary in a single trend with the magnetization time. Instead, it falls linearly first and then fluctuates slightly, with the smaller value observed at 100 s. (3) The variation trend of the viscosity with magnetic field intensity is roughly the same. It reaches the smaller value at 200 mT. Hence, the optimal combination of magnetization time and magnetic field intensity that achieves a significant viscosity reduction effect is 100 s and 200 mT. Under this combination, the viscosity of
the magnetized water decreases by 18.3% compared with the unmagnetized water.

Chen et al. (2014) concluded through experiments that the water viscosity plummets to the minimum of about 0.8 mPa·s as the magnetic field intensity increases from 0 to 170 mT, but their study did not involve a detailed discussion on the magnetization time. It can be seen from Fig. 4 that the magnetization time has a great impact on the viscosity of magnetized water. Thus, the effects of both magnetization time and magnetic field intensity should be fully considered in order to minimize the viscosity of water in the actual production process.

**Measurement of specific heat capacity**

In this paper, the specific heat capacity of water was measured by adopting the cooling method. The experimental vessel was a special calorimeter equipped with an inner cylinder and an outer cylinder. The outer cylinder which was larger was loaded with an appropriate amount of water for maintaining a constant temperature during the experiment. The temperature measurement was conducted with the aid of a UT325 contact thermometer whose manufacturer is Uni-Trend Technology (China) Co., Ltd. It can use two thermocouple probes to accurately measure the temperature in two ways at the same time. The results of the experiment are exhibited in Fig. 5.

As can be observed from Fig. 5, (1) the specific heat capacity of the water increases after magnetic treatment, indicating that magnetized water can promote the cooling efficiency under the same conditions. (2) The specific heat capacity of the water keeps growing when magnetization proceeds from 0 s to 100 s and basically remains constant after 100 s. (3) The specific heat capacity of the water differs at the same magnetization time under different magnetic field intensities. When the water is magnetized for 100 s under the magnetic field intensity of 150 mT, it reaches the maximum which is 6.28% larger than that of unmagnetized water.

**Brief summary**

Based on the above research, it can be concluded that the turning point of the change in water surface tension from gradually decreasing to steady appears when the magnetization time is 80 s, and the water surface tension is smaller as a whole when it is magnetized under 150 mT. The turning point of the change in water viscosity from gradually decreasing to steady occurs when it is magnetized for 100 s, and the water viscosity is smaller as a whole when the magnetic field intensity is 200 mT. The turning point of the change in water specific heat capacity from gradually increasing to stable occurs when the magnetization time is 100 s. Under this condition, the specific heat capacity is larger as a whole when the magnetic field intensity is 150 mT, 200 mT. In order to find the optimal magnetization conditions, the dust removal and temperature reduction performances of magnetized water spray when the magnetic field intensity is 150 mT or 200 mT and the magnetization time lies in the range of 60–120 s will be further discussed by simulation. Figure 6 shows the variations of surface tension, viscosity and specific heat capacity of water when the magnetic field intensity is 150 mT or 200 mT.
200 mT, and the magnetization time lies in the range of 60–120 s, in which 8 groups of data to be discussed are marked with shading.

**Numerical simulation and discussion**

Computational fluid dynamics (CFD), a branch of numerical simulation and analysis on convective mechanics problems using electronic computers and discrete numerical methods, can simulate the working conditions under complex conditions and reproduce the actual working conditions as much as possible. Considering this fact, the spray field was simulated with ANSYS Fluent to explore the influence of changes in water on the particle size, concentration, and temperature reduction performance of spray.

**Geometric models and mesh generation**

SCDM in ANSYS was used to draw the geometric model. The length, width, and height of the geometric model in the x-direction, the y-direction, and the z-direction were 6 m, 4 m, and 3.5 m, respectively, and the nozzle was located at a position of 3 m in length, 2 m in width, and 3.5 m in height.

Mesh generation is a critical step in numerical simulation. The adoption of reasonable mesh can enhance the efficiency and accuracy of numerical calculation. To ensure that the calculation results do not change with the number of grids, it is necessary to test the grid independence (Wang et al. 2017b). In this paper, five unit grid sizes, namely, 40 mm, 60 mm, 80 mm, 100 mm, and 120 mm, were set up, and the average grid masses were all greater than 0.8. Three sampling points on the central axis plane were selected to compare the cooling effect of unmagnetized water spray under the five unit grid sizes, and the results are listed in Table 1. It can be found that the differences in temperature at the same sampling point are less than 1 k for the grid sizes of 80 mm, 100 mm, and 120 mm, which indicates that these three grid schemes have met the requirements of grid independence. In comprehensive consideration of both the requirements of calculation accuracy and the computing resources, 80 mm was finalized as the unit grid size for calculation, and the meshing results are illustrated in Fig. 7.

**Setting of numerical simulation conditions**

The boundary conditions and specific particle parameters of the spray source were set based on the above results of experiments on the magnetized water’s dust removal and temperature reduction performances (Table 2). The droplet mass flow rate was set to 0.15 kg/s in the light of Feng (2019) and Yin et al. (2019), and the nozzle diameter was set to 2.4 mm with reference to the research on the optimal spray parameters by Liu et al. (2019c).

The pressure-swirl atomizer is used in this article, which has simple structure and better atomization effect. The fluid rotates at high speed under the action of centrifugation when it enters the swirl chamber. The fluid forms a hollow conical liquid film at the outlet of the nozzle after it is accelerated at the shrink segment. The liquid film is then further atomized under the action of pneumatic and crushes into a wire or droplet (Jiao 2019). The process of liquid from internal fluid to complete atomization is divided into three steps: film formation, sheet breakup, and atomization. The structure of pressure-swirl atomizer is shown in Fig. 8.

**Analysis of numerical simulation results**

The pressure of the nozzle is one of the main factors affecting the crushing effect of droplets in addition to the surface tension and viscosity of water. Therefore, it is necessary to consider the influence of the injection pressure of the nozzle when using Fluent software to simulate the dust removal and temperature reduction coupling performances of water spray. After the optimum injection pressure is determined, the surface tension and viscosity parameters of water in Fluent software are changed, and the parameters such as droplet size of each magnetized water are calculated, and the effect of magnetization on dust reduction performance of water is analyzed. Then the cooling effect of magnetized water is simulated, and

| Interval size (mm) | The numbers of grids | Temperature (k) |
|-------------------|----------------------|-----------------|
|                   |                      | X = 3 m | X = 4 m | X = 5 m |
| 120               | 1584                 | Divergence |         |         |
| 100               | 84000                | 301.2   | 298.4  | 296.5  |
| 80                | 165000               | 298.8   | 295.2  | 294.3  |
| 60                | 395300               | 299.1   | 294.6  | 293.8  |
| 40                | 1320000              | 299.2   | 294.8  | 293.7  |
finally the magnetization conditions with the best coupling performances of spray dust removal and temperature reduction are determined through comprehensive analysis.

**Influence of injection pressure on spray field**

The injection pressure was set from 2 MPa to 5.5 MPa (pressure interval 0.5 MPa) to analyze the changes in the droplet size and spray concentration of unmagnetized water. The condition under which the droplet size is smaller and meanwhile the spray concentration is higher is the optimal choice. The simulation results are shown in Fig. 9.

Figure 9 shows that the spray concentration presents the same variation trend under different injection pressures: On the jet centerline, the spray concentration gradually increases from the nozzle outlet to the roadway floor. The spray concentration decreases gradually from the center to the edge of the jet. This is because the first atomization occurs at the nozzle outlet, part of the jet not being completely atomized. With the increase of the distance from the nozzle, the spray is broken up again, the water being completely atomized into liquid particles. Resultantly, the concentration of spray jumps. Finally, the spray spreads around, and its concentration gradually decreases under the action of airflow and pressure.

As the injection pressure rises from 2 to 5.5 MPa, the spray concentration gradually increases. Specifically, as the injection pressure is raised from 2 to 4 MPa, the spray fields formed at different injection pressures show distinct color differences, indicating that the spray concentration changes remarkably with the increase of injection pressure in this pressure range.

| Item                  | Name                              | Parameter               |
|-----------------------|-----------------------------------|-------------------------|
| **Boundary condition**| Inlet boundary type               | Velocity-inlet          |
|                       | Outlet boundary type              | Outflow                 |
| **Dispersed phase**   | Interaction with continuous phase | On                      |
|                       | Number of continuous interaction per | 10                      |
|                       | DPM Iteration                     |                         |
|                       | Max number of steps               | 5000                    |
|                       | Drag law                          | Spherical               |
| **Spray**             | Material                          | Water liquid            |
|                       | Injection type                    | Pressure-swirl atomizer |
|                       | Upstream press (MPa)              | 5                       |
|                       | Injection inner diameter (mm)     | 2.4                     |
|                       | Flow rate (kg/s)                  | 0.15                    |
| **Computation model** | Spray half angle (degrees)        | 20                      |
|                       | Turbulence model                  | Standard k-ε model      |
|                       | Energy                            | Off                     |
|                       | Pressure-velocity coupling equation | Coupled                |
As the injection pressure continues to increase from 4.5 to 5.5 MPa, the color differences among the spray fields are slight, demonstrating that the spray concentration tend to level off after the injection pressure exceeds 4 MPa.

Aiming at further revealing the statistical rules and evaluating the atomization quality, five parameters were introduced: linear mean diameter D10, area mean diameter D20, volume mean diameter D30, volume-surface mean diameter D32 and Herdan mean diameter D43 (Wang et al. 2015). The various mean diameters of droplets in the spray field formed at different injection pressures were then calculated (Fig. 10).

Liu et al. (2019b) studied the effects of spraying pressure and nozzle orifice diameter on the atomizing rules of spraying system, and they chose to use the same pressure-swirl atomizer as in this paper. The numerical simulation shows that when the spray pressure is 1–5.5 MPa, the range of D10, D20, D30, D32, and D43 of the droplets is 57.4–516.3 μm, which is similar to the results obtained in this paper. In addition, Shi et al. (2019) studied the effect of atomization pressure on the atomization effect of pressure-swirl atomizer. The data of D32 obtained by numerical simulation are similar to those in this paper. In order to verify the accuracy of the numerical simulation results, they measured the droplet size at different positions of the atomization field by using the Mastersizer. Therefore, it can be considered that the numerical simulation results obtained in this paper are reliable.

The decrease of droplet size decelerates as the injection pressure increases. Besides, when the injection pressure is higher than 5 MPa, the droplet atomization is relatively sufficient. But the high injection pressure reduces the atomization cone angle and droplet coverage (Zhou 2019); the droplets have higher speed; and the disturbance from air enhanced, which increases the collision probability between droplets and makes the droplet size slightly increase.

The smaller the spray particle size, the greater the chance of contact with dust and the better the dust removal effect. In conclusion, the ideal injection pressure for spray dust removal is 5 MPa.
Analysis of dust removal performance

Since the nozzle diameter, water consumption, injection pressure, and atomization mechanism do not change after water magnetization, the spray concentration remains almost unchanged. However, the droplets size is no longer the same, because difficulty in water fragmentation has changed due to the variations of surface tension and viscosity. Therefore, the water spray fields under eight kinds of magnetization conditions were simulated to obtain the droplet size distribution. D32 and max diameter are selected to characterize the variation of droplet size (Fig. 11). Due to the same mass of water supply, the smaller the value of D32, the larger the surface area of droplets (Balaga et al. 2021) and the greater the chance of contact with dust. Thereby, the spray performs better with regard to dust removal.

From Fig. 11, the droplet size is reduced after magnetization. Specifically, in terms of D32, case 1 is the smallest, followed by case 2, with the difference being only 8 μm. However the max diameter of case 2 is smaller, which suggests that the droplet size of case 1 is distributed more uniformly. In terms of max diameter, case 2 and case 7 are relatively small, but the mean diameter of case 7 is about 10% larger than that of case 2. In summary, the optimal condition for dust removal is case 2, i.e., magnetic field intensity 150 mT and magnetization time 80 s. After magnetization, the mean diameter and max diameter are reduced by 39% and 16%, respectively; the chance of contact among droplets and dust particles being greatly promoted.

Analysis of temperature reduction performance

If the specific heat capacity of water is larger, the water will heat up more slowly after absorbing the same amount of heat, which is beneficial to promoting the cooling efficiency. As can be seen from Table 1, the specific heat capacity in case 2 is the largest. According to the analysis of the previous section 4.2.3, case 2 is also the optimal condition for dust removal. This makes case 2 the best condition for the coupling performances. Next, the temperature reduction effects of magnetized and unmagnetized water were simulated. The air temperature and spray temperature were set to 308 K and 293 K, respectively. Meanwhile, it is considered acceptable that the temperature in the roadway is lower than 299.15 K stipulated in the Coal Mine Safety Regulations. Main parameters for the cooling simulation of the magnetized water are shown as Table 3. The temperature distribution on the central axis of Y = 2 m is presented in Fig. 12.

When unmagnetized water is used for temperature reduction at the wind speed of 0.2 m/s, the isotherm is dense, and the heat difference is larger at the height of 2.5–3.5 m. The reason is that the small-sized droplets extend to the exit direction of the roadway under the action of wind force and the temperature drops rapidly under this condition. However, the temperature increases a bit at 2–2.5 m where the droplet concentration is lower because most of the droplets are ejected obliquely downward under pressure. In contrast, when magnetized water is used for temperature reduction at this wind speed, the isotherm is sparse, and the temperature drops to an acceptable range at locations 3 m or below. This is because the particle size of droplets formed after magnetization is small and uniform and the concentration distribution of droplets does not experience obvious stratification under the action of wind.

When the wind speed is 0.4 m/s, the temperature-reducing advantage of magnetized water spray is relatively limited.

| Name                   | Parameter                  |
|------------------------|-----------------------------|
| Inlet boundary type    | Velocity-inlet             |
| Outlet boundary type   | Pressure-outlet             |
| Energy                 | On                          |
| Turbulence model       | Realizable k-ε Model        |
| Species transport      | On                          |
| Inlet air temperature (K) | 308                      |
When the wind speed is 0.6 m/s, although the small-sized droplets in unmagnetized water move rapidly with the wind, most of the droplets are still ejected downward, leading to the existence of a high-temperature area that is 3–5.5 m long and 0.8–1.8 m high. When the workers work in this area, the high temperature will affect their health. After magnetized water is applied, despite a temperature rebound in this area, the temperature is still maintained at 299 K or below, which demonstrates that the temperature-reducing advantage of magnetized water spray is acceptable.

When the wind speed continues to increase, for example, to 0.8 m/s or 1 m/s, the small-sized droplets move quickly with the wind flow, which can hardly cool the roadway. And the large-sized droplets also move under the action of wind, but they fail to cover a large area. In this case, additional measures should be taken to promote the temperature reduction efficiency.

When the wind speed is high, more nozzles were added, and the spray concentration was raised so as to lower the temperature of the working area to an acceptable level. Nozzles were set at \( X = 0.5 \) m, 2 m, 3.5 m, and 5 m, respectively. In the meantime, the mass flow rate and the injection pressure of the spray were also increased (Table 4). The previous analysis shows that the temperature reduction effect of magnetized water is superior to that of unmagnetized water, so the discussion is merely made on the former at high wind speeds. The temperature distribution on the section of \( Y = 2 \) m is demonstrated in Fig. 13.

When the wind speed is 1 m/s, the isotherms at \( X = 2 \) m, 3.5 m, and 5 m are approximately striped. This suggests that the

![Fig. 12 Temperature reduction effects before and after water magnetization (unit: K)](image)

| Wind speed (m/s) | Mass flow rate (kg/s) | Injection pressure (MPa) |
|-----------------|----------------------|-------------------------|
| 2               | 0.2                  | 5                       |
| 3               | 0.3                  | 5                       |
| 4               | 0.4                  | 6                       |
| 5               | 0.5                  | 6                       |
| 6               | 0.6                  | 6                       |
movement range of spray shrinks under the action of the airflow since the spray concentration has been boosted by adding nozzles. And the heat in the surrounding environment is absorbed enough so that the temperature drops to 299 K or below within the allowable range.

As the wind speed continues to increase, the range of spray movement along with the airflow expands. At this time, 0.5-m-long branch pipes were connected under the pipes at the top of the roadway to reduce the temperature in the working area. In this way, the nozzles were arranged at the height of 3 m. The layout of the nozzles is shown in Fig. 14.

When the wind speed is 2 m/s, except for the front triangle area 0–1 m in height and 0.5–2 m in length where the temperature reduction effect is poor, the temperature in other working areas drops to 299 K or below. When the wind speed is 3 m/s, the range of spray movement continues to expand, and almost no heat is absorbed in the area below 1.5 m in height and 0.5–3 m in length. When the wind speed is 4–6 m/s, although the mass flow rate and injection pressure of the spray both increase, the isotherms are sparse, and the temperature difference is large within the height range of 1.5–3.5 m, indicating that there are relatively few sprays within this range because they are mainly ejected downward under the action of gravity and pressure at this time; besides, the temperature in the front triangle area below 1.5 m in height and 0.5–4 m in length does not fall, suggesting that the downward spray moves for a longer distance with the airflow. Therefore, in actual work, if the wind speed is high, it is recommended to set the first nozzle at about 3.5 m in front of the

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**Fig. 13** Temperature distribution at high wind speeds (unit: K)

**Fig. 14** Schematic diagram of nozzle layout at high wind speeds
working area to ensure that the temperature in the working area drops to an acceptable level.

**Spray system design**

A conclusion can be drawn based on the above experiments and numerical simulation: The magnetic field intensity and magnetization time have a great influence on the particle size of droplets and the specific heat capacity of water. Therefore, the spray system must have the ability to strictly control the magnetization conditions in the hope of endowing the magnetized water with excellent dust removal and temperature reduction performances. To achieve this goal, a spray system was designed (Fig. 15).

The spray system consists of a water treatment device, a pressure regulator, nozzles, water pumps, a controller, etc. The water treat device whose magnetization conditions are controllable is composed of several sections of magnetized pipes (the number of magnetized pipes is determined by the required magnetization time). Magnets with required magnetic field intensities are installed symmetrically on both sides of each section of the pipe. Shielding layers are set at the outside of magnets to ensure that the water only gets magnetized within the magnetized pipe.

According to the discussion on the temperature reduction performance of magnetized water, the mass flow rate and nozzle pressure of the designed spray system should reach 0.6 kg/s and 6 Mpa, respectively, and the water temperature should be controlled at 20°C or below. Hence, the water source should be able to provide of water at the rate of 40 L/min, and the water can be cooled by measures like adding ice when its temperature exceeds 20°C. The rated flow rate of the water pump is 44 L/min, and the rated water pressure is 8 Mpa. The flowmeter and the controller are set at the back end of the water pump to monitor the water flow data in real time and adjust the power of the water pump, in order to obtain the required mass flow rate and control the magnetization time of the water. In addition, a pressure regulator and a pressure gauge (range 0–10 MPa) are set at the front of the nozzle to adjust the pressure to the working pressure.

Reasonable selection of high-pressure water supply network parameters is crucial for the spray system. It also provides a basis for enterprises to choose suitable water supply pipes. A seamless copper pipe is adopted in the high-pressure magnetized water spray system to minimize the influence on the magnetic field, and a seamless steel pipe is adopted in the rest parts. The parameters of the spray system are listed in Table 5.

**Conclusions**

In this paper, through experimental research, the optimal magnetization conditions under the single factors of water surface tension, viscosity, and specific heat capacity were obtained, respectively. Then, simulated by ANSYS Fluent, the optimal magnetization condition for achieving the coupling performance was selected. Finally, a spray system was designed to control the magnetization condition strictly. Based on the above research, the following main conclusions were drawn:

1. When the water is magnetized under a magnetic field intensity of 150 mT for 80 s, the surface tension reaches the minimum which is about 8.5% smaller than that of unmagnetized water. When it is magnetized under 200 mT for 100 s, the viscosity of water is the lowest. Compared with unmagnetized water, the viscosity of magnetized water decreases by 18.3%. When the water is magnetized under 150 mT for 100 s, its specific heat capacity reaches the maximum which is 6.28% higher than that of unmagnetized water.

2. When the injection pressure is 5 MPa, the spray particle size of unmagnetized water is smaller, and the spray concentration is higher. Under this pressure, when the water is magnetized under 150 mT for 80 s, the mean
diameter and max diameter of magnetized water droplets are reduced by 39% and 16%, respectively. The particle size of the droplets is smaller and more uniformly distributed, which improves the dust reduction performance.

(3) When the water is magnetized under 150 mT for 80 s, the specific heat capacity of magnetized water also reaches the maximum. After it is used for temperature reduction at the wind speed of 0.6 m/s or below, the temperature in the working area of the roadway falls to an acceptable level. When the wind speed is in the range of 1–2 m/s, the working area in the roadway can be reduced to 299 K or below by adding nozzles and raising mass flow rate. When the wind speed is in the range of 3–6 m/s, the temperature can be lowered to an acceptable level by setting the first nozzle at about 3.5 m in front of the working face and properly increasing the injection pressure.

Author contribution Chengfeng Wang is a major contributor in performing the experiments, running the CFD simulations, and writing the manuscript. Mingjie Li finished the data collection and collation. Shouqing Lu designed and gave the main structure of the manuscript and the financial support for this manuscript. Yongliang Zhang, Zhanyou Sa, Jie Liu, Hao Wang, and Shengcheng Wang contributed to the final manuscript. All authors read and approved the final manuscript.

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Data Availability Not applicable.

Table 5 Parameters of the spray system

| Number | Part names | Parameters |
|--------|------------|------------|
| 1      | Water source | Can provide 40 L/min water, the temperature is not higher than 20°C |
| 2      | Water pump   | Rated flow rate 44 L/min, rated water pressure 8 MPa |
| 3      | Pressure regulator | Can adjust the pressure to work pressure |
| 4      | Pressure gauge | The range of 0–10 MPa |
| 5      | Valve        | Used to control the flow of water in pipelines |
| 6      | Flowmeter    | Real-time monitoring of water flow |
| 7      | Controller   | Cooperate with flow meter to control the power of water pump |
| 8      | Magnet       | The magnetic field strength is 150 mT |
| 9      | Shielding layer | 500 kHz Magnetic shielding material |
| 10     | Nozzle       | Pressure-swirl atomizing nozzle |
| 11     | Water pipe 1 | Φ 30 × 2.5 mm Seamless steel pipe |
| 12     | Water pipe 2 | Φ 32 × 2 mm Seamless copper tube |

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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