Study on the influence of airflow disturbance on spray atomization

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Abstract: The droplet distribution characteristics are one of the key factors that determine the dust suppression effect of spray system. In order to study the droplet distribution characteristics under different working conditions, the influence mechanism of wind speed and spray angle on droplet distribution characteristics was studied based on Fluent software. The results show that the increase of wind speed and spray angle will increase the lateral momentum of droplets, resulting in the increase of longitudinal height and lateral length of spray belt. The change of spray angle causes the change of the distribution ratio of transverse momentum and longitudinal momentum of droplets. With the increase of spray angle, the transverse momentum of droplets increases and the longitudinal momentum decreases, resulting in the increase of the longitudinal height and length of spray belt. In engineering practice, attention should be paid to the coordinated control of nozzle height, spray angle and airflow speed.

Keywords: Spray dust suppression; Wind disturbance; Coal mine dust; Mass concentration distribution; numerical simulation

1. Introduction

In order to control underground dust, scholars have developed many dust control technologies, including wet spraying [1], local ventilation [2], air curtain isolation [3] and personal protective equipment [4]. Considering environmental protection and cost, dust control technologies based on water media have attracted the highest attention, such as coal seam water injection technology [5], which is low in cost, but it is difficult to achieve the expected effect due to poor permeability of coal seam [6] At present, spray dust suppression technology is the most widely used dust suppression technology [7-9]. One is internal spraying, that is, spraying near the cutting teeth of the shearer, wetting the coal body during the cutting process, and then controlling the dust from the source. The second is external spraying, which forms a spray field around the coal mining drum and uses droplets to capture coal dust particles. Coal dust contains a large number of hydrophobic functional groups such as aliphatic hydrocarbons and aromatic hydrocarbons, which increases the difficulty of capturing coal dust by aqueous solution. In order to improve the wettability and dust removal efficiency of spray solution, scholars have carried out a lot of research on spray solution for coal mine dust removal. The results show that surfactants can significantly improve the wettability of the solution, but the addition of surfactants will increase the viscosity of the solution, which is not conducive to the breakup and dispersion of droplets.

In addition to solution properties, nozzle size, spray pressure and air flow conditions are also key factors affecting droplet distribution and dust suppression effect. Scholars have done a lot of research on this, for example, Zhou et al. [10] studied the influence of water pressure and nozzle diameter on spray atomization effect, and optimized the configuration parameters of water pressure and nozzle diameter. Ren et al. [11] first studied the distribution law of spray field along the airflow direction, and developed a new dust removal spray system based on this. In order to obtain better atomization effect, some scholars use water and air to spray together, and the sprayed air makes the droplets be broken twice, which further enhances the turbulence of the sprayed liquid. However, because air-water spray needs compressed air, but the space of underground cable trench is limited, it is difficult to lay gas supply pipeline in coal mining face. Therefore, it is difficult to apply air-water spray dust control technology to coal dust control in coal mines.

Generally speaking, in addition to nozzle size, spray pressure, droplet composition and other factors, airflow conditions are also an important factor affecting droplet distribution characteristics, and also a key factor determining the effect of spray dust suppression. Due to ventilation needs, underground airflow parameters are complex and changeable, and the influence of airflow conditions on spray dust suppression effect becomes complicated. Therefore, the influence of airflow conditions on droplet distribution characteristics of spray dust suppression system is a necessary prerequisite for accurate adjustment of spray parameters. In addition, the cost of underground experiments is high, which affects the normal coal mining work. The numerical simulation research based on CFD can effectively solve this problem. Based on this, this study uses Fluent software to systematically study the influence law of airflow conditions such as wind speed and airflow angle on spray droplet distribution under different spray pressures, and clarify the mechanism of airflow on spray droplet distribution. The research results can provide a theoretical basis for optimizing the parameters of spray dust suppression system in coal mine.

2. CFD simulation method

2.1 Numerical method

The discrete phase model in Ansys Fluent follows Euler-Lagrange method. The model describes the continuous flow field by solving Navier-Stokes equation, and the discrete phase tracks the force balance of particles in Lagrange coordinate system through the calculated flow field to predict the motion rules of particles. The force balance can be expressed as:

$$m_p \frac{d\vec{u}_p}{dt} = m_p \frac{\vec{u}-\vec{u}_p}{\tau_r} + m_p \frac{\overrightarrow{g(\rho_p-\rho)}}{\rho_p} + \vec{F} \quad (1)$$

Where m_p is the particle mass, u is the fluid phase velocity, u_p is the particle velocity, ρ is the fluid density, ρ_p is the particle density, $\vec{F}$ is the additional force, $m_p \frac{\overrightarrow{u-u_p}}{\tau_r}$ is the resistance, and τ is the relaxation time of the droplet.

Firstly, the amplitude of undamped oscillation of each droplet is determined, which is expressed as:

$$A = \sqrt{(y^n - We_c)^2 + \left(\frac{(dy/dt)^n}{\omega}\right)^2} \quad (2)$$

$$We_c = \frac{C_F}{C_k C_b} We \quad (3)$$

$$y = x/(C_b r) \quad (4)$$

Where x is the displacement, ω is the oscillation frequency of the droplet, and C_F 、 C_k and C_b are three dimensionless numbers, which are 8, 5 and 1/3 respectively.

When $We_c + A > 1$, the droplet breaks.

1.2 Simulated conditions

In order to observe the droplet distribution characteristics of the water curtain dust suppression system in detail, the spray dust suppression system is simplified as a single nozzle, with a spray angle of 45 and a water pressure of 3 MPa. A geometric model is established by using the ICEM module of ANSYS. The calculation domain is set as a cube with a height of 5.4*5.4*5.4 m, and the nozzle is set at the center with a height of 3 m..In order to observe the droplet distribution characteristics of the water curtain dust suppression system in detail, the spray dust suppression system is simplified as a single nozzle, with a spray angle of 45 and a water pressure of 3 MPa. A geometric model is established by using the ICEM module of ANSYS. The calculation domain is set as a cube with a height of 5.4*5.4*5.4 m, and the nozzle is set at the center with a height of 3 m, as shown in Table 1.

Table 1 Calculation parameters

serial number	wind speed (m/s)	Spray angle
1	0.5	30°
2	1	30°
3	1.5	30°
4	2	30°
5	3	30°
6	4	30°
7	1.5	15°
8	1.5	45°
9	1.5	60°

3. Results and discussion

3.1 Distribution characteristics of airflow field

The distribution characteristics of airflow field in roadway is an important factor affecting spray diffusion and droplet size, which further affects the dust suppression effect of spray. Therefore, it is necessary to systematically study the distribution characteristics of airflow field under different conditions before studying the disturbance behavior of airflow conditions on spray. In this section, the distribution characteristics of airflow field under different wind speeds (0.5 m/s, 1 m/s, 1.5 m/s, 2 m/s, 2 m/s and 4 m/s) and different spray angles (15°, 35°, 45° and 65°) are mainly analyzed.

Figure 1 shows the distribution of velocity field at different wind speeds when the spray angle is 30. As can be seen from the figure, the existence of spray has obviously disturbed the flow field, and the disturbance degree and disturbance range of spray to the air flow field reflect the movement speed and diffusion range of droplets. Because the high-speed spray from the nozzle drives the air to accelerate, an obvious strip-shaped high-speed flow field is produced downstream of the nozzle. Because of the shielding effect and reflection effect of spray belt on airflow, a low-speed zone is formed around the long high-speed flow field. When the wind speed is 1.5 m/s, such a low-speed region is most obvious. With the increase of wind speed, the speed and width of the strip high-speed flow field increase, and the drift angle decreases gradually (the angle with the bottom plate). This shows that with the increase of wind speed, the diffusion speed of droplets will be improved, but the diffusion range will be reduced.

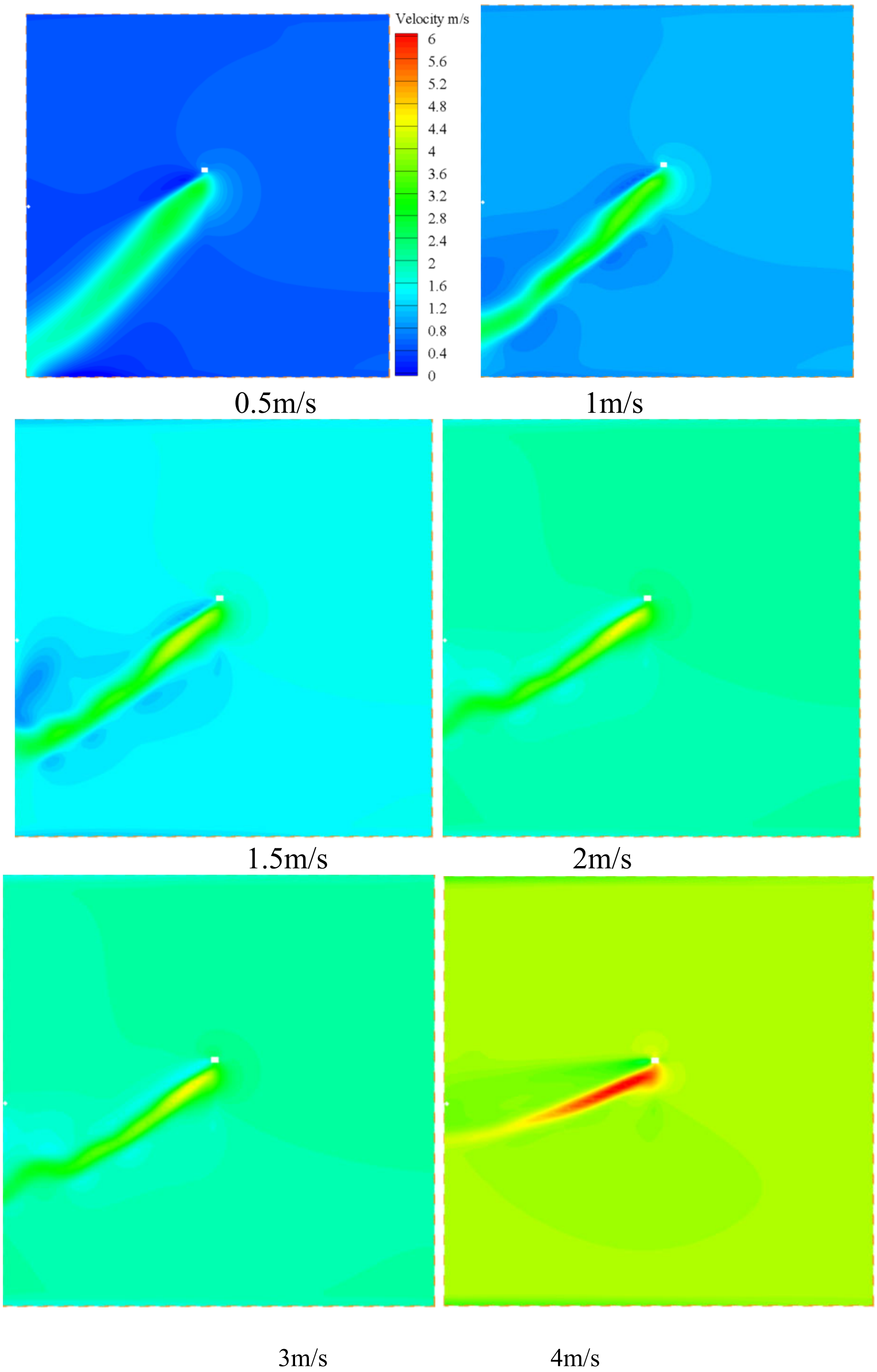

Fig. 1 Cloud map of velocity field distribution under different wind speeds

Fig. 2 shows the velocity field distribution at different spray angles when the wind speed is 1.5 m/s. As shown in the figure, increasing the spray angle has a similar effect to increasing the wind speed, that is, with the increase of the spray angle, the spray belt will get a higher moving speed, but its diffusion range will be reduced. On the other hand, with the increase of spray angle, the angle between spray direction and airflow direction becomes smaller, and the shielding range and reflection range of spray belt to airflow gradually shrink, resulting in the area of low-speed zone around spray belt gradually shrinking.

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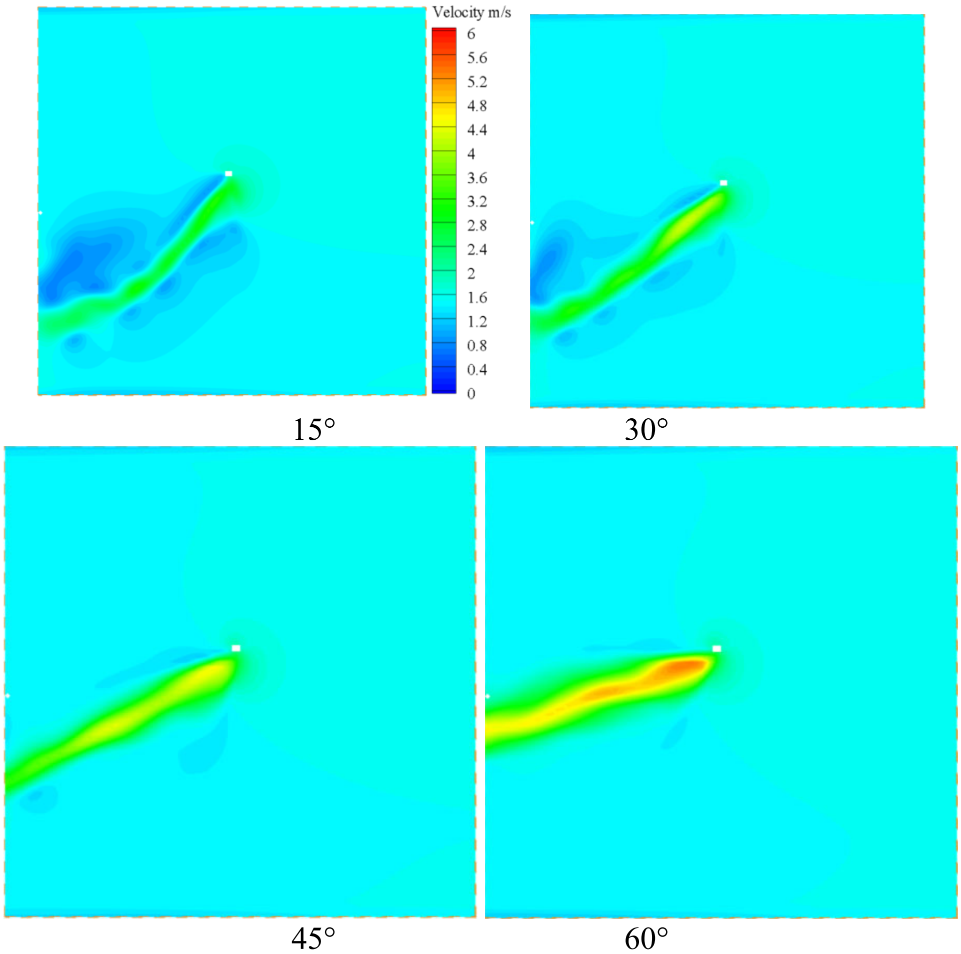

Fig. 2 nephogram of velocity field distribution at no spray angle

3.2 Influence of spray angle on droplet distribution characteristics

Spray angle is one of the important parameters of water curtain dust suppression project in roadway, which determines the direction of droplet exit momentum and is the key factor to determine spray diffusion characteristics. Therefore, this section focuses on the distribution characteristics of droplet mass concentration at different spray angles when the wind speed is 1.5 m/s.

Fig. 3 is a nephogram of mass concentration distribution at different spray angles when the wind speed is 1.5 m/s. As can be seen from the figure, with the increase of spray angle, the droplet distribution in the human respiratory zone gradually decreases. When the spray angle is 45, the droplet mass concentration in the human respiratory zone is only about 0.03 kg/m3. On the other hand, it can be seen from the distribution of droplet mass concentration at the longitudinal section of the nozzle that when the spray angle is 15, some vortex structures are formed at the tail of the spray belt, and with the increase of the spray angle, the vortex structures gradually weaken until they disappear. This is mainly because when the spray angle is small, a large area of low-speed zone appears downstream of the spray belt, which forms an obvious speed difference with the lower part of the spray belt, and at the same time, the angle between the momentum direction of the spray outlet and the airflow direction is large, thus causing the droplet trajectory to show a vortex state. However, when the spray angle is large, the included angle between spray outlet momentum and airflow momentum is small, and the droplet trajectory is mainly controlled by lateral momentum, and the longitudinal momentum has no obvious disturbance to the droplet trajectory.

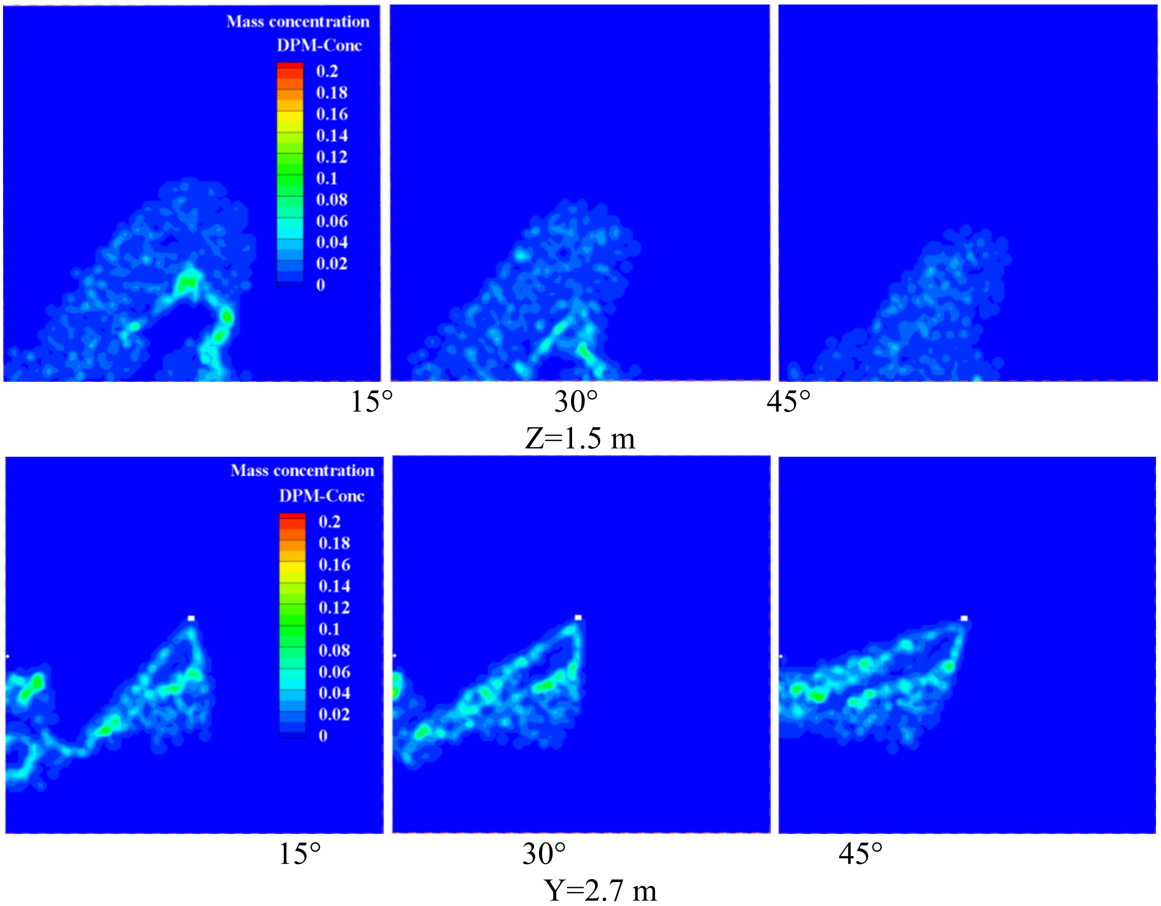

Fig. 3 nephogram of droplet mass distribution at no spray angle

4. Conclusion

The velocity distribution characteristics of airflow field are controlled by spray and airflow conditions. With the increase of spray angle and airflow speed, the lateral momentum increases, which leads to the obvious increase of spray zone velocity and the obvious decrease of spray zone area. The change of spray angle causes the change of the distribution ratio of transverse momentum and longitudinal momentum of droplets. With the increase of spray angle, the transverse momentum of droplets increases and the longitudinal momentum decreases, resulting in the increase of longitudinal height and length of spray belt, but the particle size distribution has no obvious change.

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References

1. DING X, MA T, ZHAO W, et al. Airborne high oil-content coal particles suppression via the electrolyte accelerated application of hydrocarbon and short-chain fluorocarbon surfactants[J]. Fuel (Guildford), 2023, 332:126192.
2. ZHANG W, XUE S, TU Q, et al. Study on the distribution characteristics of dust with different particle sizes under forced ventilation in a heading face[J]. Powder Technology, 2022, 406:117504.
3. XIU Z, NIE W, CAI P, et al. Partially enclosed air curtain dust control technology to prevent pollution in a fully mechanized mining face[J]. Journal of Environmental Chemical Engineering, 2022, 10(5):108326.
4. GE X, CUI K, MA H, et al. Cost-effectiveness of comprehensive preventive measures for coal workers' pneumoconiosis in China[J]. BMC Health Serv Res, 2022, 22(1):266.
5. LIU Z, CAO A, GUO X, et al. Deep-hole water injection technology of strong impact tendency coal seam—a case study in Tangkou coal mine[J]. Arabian journal of geosciences, 2018, 11(2):1-9.

6. LU X, WANG D, SHEN W, et al. Experimental investigation of the pressure gradient of a new spiral mesh foam generator[J]. Process Safety and Environmental Protection, 2015, 94:44-54.
7. OTGANISCAK J A, KLIM S S, POLLOCK D E. Empirical engineering models for airborne respirable dust capture from water sprays and wet scrubbers[J]. Min Eng, 2018, 70(10):50-57.
8. CAO L. Experiment and effect analysis of dust suppression by spray atomization in coal mine [J]. Mechanical management and development, 2023,38 (09): 20-21.
9. ZHENG L , TIAN X, WANG W. Research and application of reducing resistance and improving efficiency of dust removal system in coal mine heading face [J]. Mining safety and environmental protection, 2015,42 (05): 72-75.
10. ZHOU Q, QIN B, WANG F, et al. Effects of droplet formation patterns on the atomization characteristics of a dust removal spray in a coal cutter[J]. Powder Technology, 2019, 344:570-580.
11. REN T, WANG Z, COOPER G. CFD modelling of ventilation and dust flow behaviour above an underground bin and the design of an innovative dust mitigation system[J]. Tunnelling and Underground Space Technology, 2014, 41:241-254.