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Study on Dust Removal Technology of Explosive Water Mist in Drill and Blast Tunnelling

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Abstract

In view of the problem that high concentration of dust is easily generated during rock tunnel drilling and blasting construction, explosive water mist to reduce dust is given in this paper. Water bag is set up on tunnel face and explosive water mist is used to reduce blasting dust concentration. With the help of numerical simulation software FLUENT and combined with theoretical analysis, The key parameters of explosion fog and dust reduction technology are obtained: water bag spacing, blasting time difference, water bag layout position, etc., which provides a theoretical basis for practical application of the technology. At the same time, combined with the field test of Huangtai tunnel blasting, the dust concentration with and without water mist was measured, respectively. The results show that the maximum dust removal rate of the tunnel section under the dust removal measures with water mist can reach 80.85%, the average dust removal rate can reach 65.16%. So, the dust removal effect is remarkable.

Keywords

rock tunnel, drilling and blasting method, explosive water mist dust removal, ANSYS/FLUENT

1 Introduction

The construction space of rock tunnel is limited, and the geological conditions are extremely complex. Each operation will produce a large amount of dust in the process of drilling and blasting construction. The contribution rate of explosive dust and process dust is the most important, accounting for about 80%~90% of the total amount of dust. In addition, the tunnel has the characteristics of concealment and closure. The dust generated by blasting will diffuse in the tunnel for a long time, which not only causes harm to human health, but also affects the equipment safety and the progress of the project. Based on the principle of simplicity, economy and high efficiency, the use of water mist to reduce dust has become one of the main measures of dust control.

Wallace and Cheung [1], applied water mist dust removal to small crushers and achieved good results. Li [2], discussed the dust removal mechanism of explosive water mist, used DPIV measuring system to monitor the particle size distribution of water mist, and concluded that the relative velocity of liquid dust and the particle size of water mist would affect the dust collection efficiency of water mist. Han et al. [3], analyzed the settlement characteristics of blasting dust and applied the method of dust removal by blasting water mist in combination with the demolition of buildings. Li et al. [4] adopted water bag blocking for blasting test, and significantly reduced the concentration of blasting dust in the step blasting test of open-pit mine. Zhang et al. [5], observed and analyzed the explosion of mist from water bag at the open-air step blasting site. In the experiment, they studied the influence of different water bag diameters ϕ, different initiation charge Q and different concentration of foaming agent E on the mist formation effect of explosive water mist and obtained the key parameters for the best mist formation effect. Yang et al. [6], applied blasting water mist to dust removal in open-pit coal mines and achieved obvious results. Guo [7], conducted a visualization study on dust. The above research provides a practical method and theoretical basis for water bag parameter setting in explosive water mist dust removal. However, the application of the dust removal method of blasting water bag to generate water mist in the tunnel construction by drilling and blasting method is still in the initial stage.

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With the rapid development of science and technology and the continuous popularization and application of computer technology, using numerical simulation software to study the law of dust migration has become one of the more and more popular. As early as 1910, L. F. Richardson [8], explained the Laplace iterative method in detail, thus creating a theoretical basis for the numerical simulation of partial differential equations. Subsequently, the appearance of computer promoted the development of fluid mechanics and the leap forward of calculation methods, such as the finite difference method, which was widely used in engineering practice [9]. The simulation of water mist and dust fall based on CFD [10–14], is becoming more and more mature. Feng [15] used Fluent to conduct numerical simulation of air flow movement and dust migration rule and believed that the dust concentration on the working surface could be reduced by spraying. Jiang et al. [16], established the physical model of long-distance single-head tunnel by Fluent, and simulated and analyzed the dust migration rule during tunnel drilling ventilation. On the basis of these existing studies, this paper conducts a more detailed study on the dust reduction of explosive water mist in tunnels, makes more specific numerical simulations, and obtains more accurate conclusions.

This paper uses a combination of theory and practice. Firstly, the mechanism of water mist dust reduction is analyzed, the factors affecting water mist dust reduction are found, and the layout location of water bags in explosive water mist dust reduction is determined. Then, the key parameters of water mist dust reduction during the construction of tunnel drilling and blasting method are determined by numerical simulation. Finally, the effect of water mist dust reduction was verified by field test.

2 Theoretical analysis of water bag explosion

2.1 Atomization principle of water bag explosion

The water bag is torn and broken open under the action of explosive explosion, and the liquid is rapidly broken into liquid droplets under the combined action of shock wave and explosive gas, and then separated into water mist after strong friction with the air. Water bag blasting and misting is a process of separating into droplet groups by continuous liquid breaking, and then breaking droplets into finer water mist. It can be divided into two stages: the first crushing stage and the secondary crushing stage.

(1) The first crushing stage

The first crushing stage is when the water bag is blown apart by detonation energy. Secondly, the liquid water is broken into droplet groups. Samirant et al. [17] believes that in the first crushing stage, the water bag is rapidly disintegrated and broken at the moment of explosive explosion. A large amount of high temperature and high-pressure explosive gas is generated, and shock waves are formed in the liquid. The shock wave causes the surface tension of the liquid to be overcome and the contact surface of air and liquid to split, finally the liquid is broken into droplet groups.

At this stage, an unstable interface is formed between the air and the liquid. The instability of its interface causes the liquid to break up into droplet groups quickly.

(2) The secondary crushing stage

This stage is the main process for the droplet group to further split and break into fine water mist. The occurrence of this process is significantly related to the dimensionless characteristic parameters. Faeth et al. [18] found that the secondary fragmentation has a certain relationship with the dimensionless Weber number "We", the Ohnesorge number "Oh" and the dimensionless fragmentation time "T". The Weber number We representing the ratio of the inertia force and surface tension of the droplet particles can be calculated according to Eq. (1). The larger the number of We the larger the inertia force of mist drops. It can easily overcome the surface tension and cause secondary breakage.

$$\mathrm{We} = \frac{\rho_g d_0 U_0^2}{\sigma}, \tag{1}$$

where ρ_g is the gas density, d_0 is the diameter of the droplet in secondary breakage, U_0 is the velocity of the droplet, and σ is the Droplet surface tension.

The Oh representing the ratio of the viscous force and surface tension of the droplet particles is calculated according to Eq. (2). The higher the Oh number the greater the viscous force of the droplet, which makes the droplet less prone to secondary breakage.

$$\mathrm{Oh} = \frac{\mu_1}{\sqrt{\rho_l d_0 \sigma}}, \tag{2}$$

where μ_1 is the Dynamic viscosity coefficient of liquid, and ρ_1 is the liquid density.

When the density ratio of liquid to air is greater than 500 and Oh < 0.01, Zhang [19] research found that the crushing mode of liquid varies with the size of We number, and the changing rule is shown in Table 1.

As can be seen from the table, when the viscous force of the droplet is small and the resistance of the droplet particles is equal to the surface tension, the droplet will be broken into water mist twice. At the same time, the larger the number of We, the more severe the droplet breakage. It can be easily broken into water mist.

Table 1 Deformation and breakage modes of droplet particles with different We numbers

Number of features We	Droplet breaking mode
0 < We < 11	The vibration deformation
11 < We < 35	Pouch and broken
35 < We < 80	Mixed broken
80 < We < 350	Shear broken
We > 350	To ruin and shatter

2.2 Factors affecting explosive water mist

The process and reasons of the explosive water mist are very complicated. There are many factors affecting the height, radius, coverage and time of the spray. When the water mist reaches the longest duration and maximum coverage, the mist rate is called the optimal mist rate. Based on explosive coefficient, length-diameter ratio of water bag and surface-active agent, the paper aims to study the influence of three factors on the mist rate of water bag explosion.

(1) Explosive coefficient

Explosive coefficient K refers to the amount of explosive used per unit volume of water in the water bag, which is one of the important parameters affecting the mist characteristics of the water bag explosion [20].

$$K = \frac{Q_c}{V_w} , \tag{3}$$

where K is the explosive coefficient, Q_c is the dynamite and V_w is the Water consumption.

The results show that when the explosive coefficient is 0.37~0.65 g/L, the larger the explosive coefficient is, the larger the diffusion range and the height of the spray will be. When the explosive coefficient is 0.45~0.55 g/L, the larger the explosive coefficient is, the longer the water mist stays in the air. However, the K value should not be too large, otherwise the effect is not significant. Therefore, when the explosive coefficient is 0.45~0.55 g/L, the atomization effect of water bag blasting is the best.

(2) Length-diameter ratio of water bag

The length-diameter ratio refers to the ratio of the length of water bag to the diameter of water bag, which is an important factor reflecting the capacity of water bag, it is also an important index to measure the blasting effect of water bag into mist. Liu et al. [21], conducted blasting tests on water bags with different length-diameter ratios and measured the spraying radius of water mist. He found that the blasting effect of water bags became better with the increase of the ratio of length to diameter, the concentration and uniformity of water mist were also better.

(3) Surfactant

Surfactant has fixed hydrophilic groups and can reduce the surface tension of water. The research shows that after adding surfactants to water, the surface free energy of water is weakened, and the aqueous solution is more likely to form a large number of fine foams under the action of blasting. Zhang et al. [5], applied different surfactant concentrations in the open-pit step blasting test, the study found that the maximum height and duration of water mist increase with the increase of surfactant, when the surface activity "Es" is 5 kg/m^3, the blasting water mist rate is the best.

2.3 Determination of water bag layout position

The rock block broken by explosive energy in tunnel blasting is given a certain initial velocity and is thrown out of the tunnel face in the form of flat throwing motion. If the seepage of explosive gas is not considered, the early Chinese scholar Liang [22] compared the rock moving process after blasting to the stable eddy current motion in the flow field. The calculation formula of the average throwing velocity of the rock was obtained by hydrodynamic analysis.

$$V_m = \sqrt{\frac{2E}{M}} , \tag{4}$$

where V_m is the average throwing velocity of the rock, M is the weight of the rock thrown by the blast and E is the throwing kinetic energy of the rock.

Generally speaking, the throwing kinetic energy of the rock accounts for 14%~16% of the energy released by the explosive explosion, which can also be calculated according to the following empirical formula:

$$\begin{cases} E = \left(0.14 \sim 0.16\right) \times 4.5 \times 10^5 Q \\ Q = qW^3 \left(0.4 + 0.6n^3\right) \end{cases} , \tag{5}$$

where Q is the amount of explosive used in blasting, q is the unit powder explosive consumption, W is the minimal resistance line and n is the index of blasting action.

Suppose that the unit powder explosive consumption in a blasting is q = 0.92 kg/m^3, the minimum resistance line W = 1.5 m, and the index of blasting action n = 1.25. By calculation, the kinetic energy of the rock throwing is kg × m^2/s^2, and assuming the mass of the exploded rock throwing is 145800 kg, the average velocity of the rock throwing can be calculated between 6.48 m/s and 6.94 m/s by substituting into Eq. (4).

A particle *O* is taken from the center of the projectile rock mass, and its initial velocity is assumed to be *v*, its direction is perpendicular to the face of the rock mass. The rock block is thrown at the detonation pile in front of the tunnel face, assume that the horizontal distance between the mass center of the rock block thrown and the mass center of the detonation pile is *S*, the vertical distance between the two particles is *h*. According to the throwing theory, the blasting throwing model is established, as shown in Fig. 1.

From the moment of detonation to the floor of the tunnel, the particle is thrown out along the vertical direction of the palm plane, its motion process can be approximately regarded as flat throwing motion, that is, uniform linear motion along the horizontal direction and free-falling motion along the vertical direction [23]. It is assumed that the rock movement has one-dimensional characteristics, and the influence of air resistance on the rock movement is not taken into account. Therefore, the prediction formula of the average throwing distance of blasting pile is introduced.

$$S = V_m \sqrt{\frac{2h}{g}}, \tag{6}$$

where V_m is the average throwing velocity of the rock and *g* is the vertical distance between the two particles.

Based on the above analysis, according to the actual situation of Huangtai Tunnel based on this paper and previous reference materials, the tunnel section is a semicircle with radius of 8 m. Assuming that the height range of the centroid of the rock being thrown is 4~8 m, the average velocity V_m of the rock and the height *h* of the particle of the rock being thrown are substituted into Eq. (6).It can be calculated that the average throwing distance of the explosion pile is about 5.86~8.87 m.

It is found [24] that for different rock types, the average velocity of throwing is roughly 4.12~14.57 m/s, and the maximum velocity can reach 10.99~38.85 m/s. Therefore, influenced by various uncertain factors, the average velocity of rock throwing is uncertain, and the throwing distance of blasting pile is also variable. In order to prevent the dust removal effect from being affected by the broken rock mass during tunnel blasting, the water bag is placed at the average front position of blasting pile throwing.

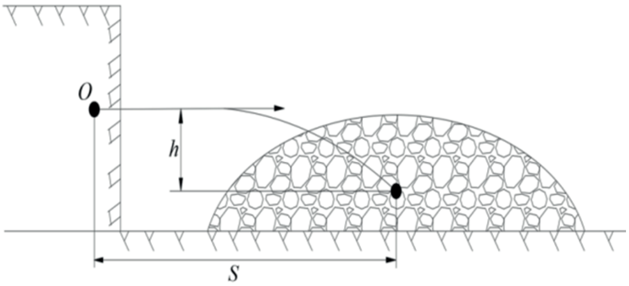


Fig. 1 Blasting throw model

The average length of the blast zone of the tunnel is 8~15 m, which is not much different from the estimated average blast distance. Other scattered flying stones can reach 15~30 m, even more than 40 m. Therefore, in order to avoid the water bag completely buried by the explosion pile, it is more appropriate to arrange the water bag 15~30 m away from the tunnel face.

3 Methodology

3.1 Numerical modeling

Due to the closed tunnel space, numerous operating equipment and complex construction environment, the tunnel model cannot be accurately restored. Therefore, combined with the actual situation and on the premise of having little influence on the numerical simulation results, in order to more conveniently establish the three-dimensional physical model of the tunnel and improve the aesthetics of the model, the dust diffusion space is properly simplified:

(1) The tunnel is simplified into a semi-cylindrical arch space with a section radius of 8m and a length of 200 m;

(2) Considering the influence of air flow in the ventilation duct on dust, the influence of other construction equipment in the tunnel on dust should not be considered;

(3) Dust generated by other construction processes and dust raised twice during blasting are not considered.

Through the above simplification, according to the actual situation of the tunnel blasting space, the Design Modeler software is used to establish the three-dimensional physical model of the tunnel in a 1:1 ratio, as shown in Fig. 2. Among them, the tunnel ventilation duct (air duct) is hung on the upper right side of the tunnel, with a diameter of 1.4 m and a distance of 3 m from the floor. The speed inlet of the ventilation duct is set at 50m from the tunnel face.

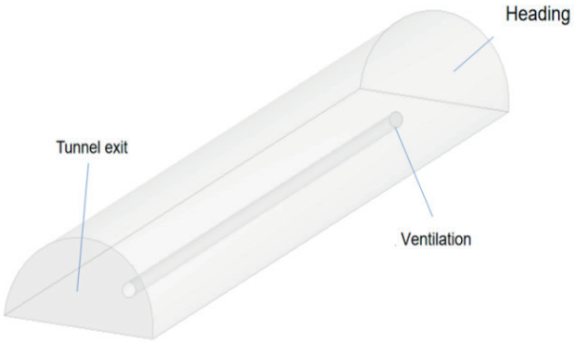


Fig. 2 Three-dimensional geometric model of the tunnel

The simplified tunnel geometry is relatively regular, so this paper uses a hexahedral structured mesh with better computational performance. The hexahedral mesh is generated by the method of hybrid division (multizone), the face size and body size are inserted at the same time to uniformly encrypt the mesh. Finally, 5 inflations are inserted, with a single inflation thickness of 50 mm. The final number of meshing units is 119940.

Through extensive reference to relevant literature and technical data of tunnel blasting dust migration characteristics and particle size distribution, combined with relevant research in the field of coal mine roadway, according to the setting requirements of discrete phase model in ANSYS Fluent software, and referring to previous research results, discrete phase model parameters, jet source parameters and boundary conditions were valued. The parameters of numerical simulation are set in Table 2 to Table 6.

Hydraulic diameter in Table 4 is calculated according to Eq. (7):

$$d_h = \frac{4A}{S}, \tag{7}$$

where A is the area of cross section and C is the Fluid and solid base girth.

Table 2 Calculation model Settings

Model	Define
Solver	Segregated
Viscous Model	k-epsilon
Energy	Off
Discrete Phase Model	On

Table 3 Discrete phase parameter Settings

Discrete Phase Model	Define
Phase coupling frequency	10
Max number of steps	20000
Length scale	1
Drag law	Spherical

Table 4 Boundary condition setting

Boundary Conditions	Define
Inlet Boundary Type	Velocity inlet
Inlet Velocity Magnitude	20 m/s
Hydraulic Diameter	1.4 m
Turbulence Intensity	2.6%
Outlet Boundary Type	Outflow
DPM Condition	Trap / Reflect
Shear Condition	No Slip

Turbulence intensity is calculated according to Eq. (8):

$$\begin{cases} I = \dfrac{u'}{\overline{u}} = 0.16(\mathrm{Re}_H)^{-\frac{1}{8}} \\ \mathrm{Re}_H = \dfrac{\rho v D_H}{\mu} \end{cases}, \tag{8}$$

where u' is the turbulent motion velocity, $\overline{u}$ is the average velocity, Re_H is the Reynolds number by hydraulic diameter, ρ is the fluid density, v is the fluid velocity and μ is the dynamic viscosity coefficient.

Wherein, the mass flow rate is calculated according to Eq. (9):

$$\text{Mass flow rate} = cvA, \tag{9}$$

where c is the dust concentration on the tunnel face,is the wind speed in the tunnel and A is the tunnel sectional area.

The main numerical simulation parameters and boundary conditions have been set up, and the specific setting details are not listed in this paper.

The blasting mist of water bag only occurs in a short time, and the diffusion space of water mist is relatively small, so it is properly simplified, and the influence of construction equipment in the tunnel is not considered. According to the requirements of the tunnel water bag blasting experiment conducted on site and the actual situation of the tunnel, the software Design Modeler is used to re-establish the three-dimensional geometric model,

Table 5 Dust source parameter Settings

Injection	Define
Injection type	Surface
Material	Dolomite
Diameter distribution	Rosin-Rammler
Min. Diameter	2.0×10^{-6} m
Max. Diameter	100×10^{-6} m
Mean Diameter	12×10^{-6} m
Spread Parameter	1.93
Velocity	0 m/s
Total Flow Rate	0.3 kg/s
Turbulent Dispersion	Stochastic Tracking
Number of Tries	1000
Time Scale Constant	0.15

Table 6 Solution parameter Settings

Solve	Definew
Pressure Velocity Coupling	SIMPLE
Discretization Scheme	Second Order Upwind
Convergence Criterion	10^{-3}

as shown in Fig. 3. Among them, the tunnel is a semi-cylindrical arched space with a radius of 8 m and a length of 30 m. The water bag is regarded as a semi-cylinder with a diameter of 30 cm and a length of 10 m. The first and second water bags are arranged 10 m and 15 m away from the tunnel face, respectively.

Due to the small volume of the water bag, the short time and small diffusion space of the water bag blasting to spray the mist, the mesh needs to be finely divided, the calculation results are more accurate, and the simulation effect is more real. Mesh software was used to mesh the tunnel water bag blasting model, which is divided into tetrahedral mesh. Finally, the number of units divided is 325275, the average element quality is 0.845, the average mesh skewness is 0.215, and the average Jacobian ratio is 0.837. The grid division is shown in Fig. 4.

3.2 Field trial arrangement

Due to the construction schedule in the tunnel, when the dust has not completely dissipated, it is necessary to enter the tunnel for the next construction process. Although there are protective measures, the effect is limited. The dust removal idea proposed in this paper is to lay a water bag at the front of the tunnel face, generate sufficient water mist through the explosive water bag to fully wrap the dust generated by tunnel blasting for dust removal. Guided by numerical simulation to set reasonable water bag spacing, initiation time difference, explosive coefficient and layout position.

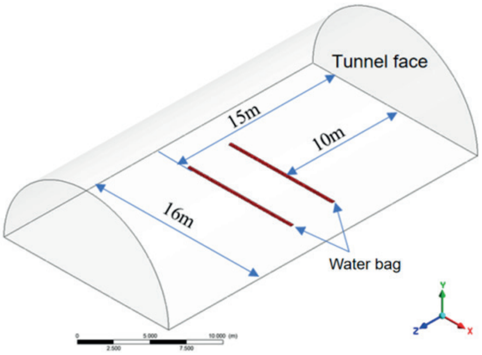


Fig. 3 3D model of tunnel blasting water bag

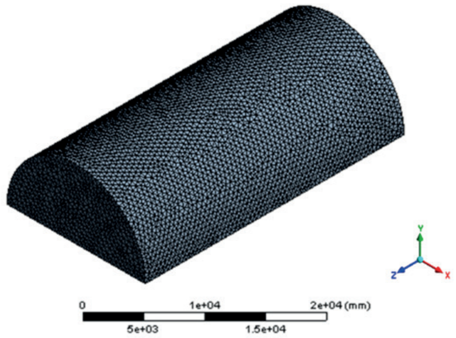


Fig. 4 3D grid of tunnel blasting water bag model

The length of the line is AK23+635, the distance from the entrance is 2155 m, the distance from the exit is 1859 m, the total length of the inclined shaft is 462 m, and the longitudinal slope of the inclined shaft is 6%. At the time of this test, the tunnel has been excavated to about 285 m away from the entrance. Based on the results of numerical simulation and theoretical analysis, the final test scheme and monitoring method are determined.

The tunnel is drilled by YT-28 gas leg drilling drill with a diameter of 42 mm. Blasting equipment selected Φ = 32 mm water-resistant two rock emulsion explosive. Electronic digital detonator and Φ = 6 mm double copper core foot wire are used. They are all connected with special detonator excitation. The peripheral holes shall be charged with intervals and general industrial detonating cords shall be used. This design tunnel III level rock single cycle blasting is 2.5 m, the utilization rate of the gun hole is 80%, the depth of the gun hole is 3 m.

(1) Test purpose

Firstly, the dust concentration with and without explosive water mist dust removal measures are measured by monitoring the concentration of blasting dust in tunnel construction and the dust removal efficiency of explosive water mist dust removal technology is explored. Secondly, the feasibility of numerical simulation results is verified.

(2) Layout position of water bag

Considering that there are two piles of ballast on the two sides of the tunnel 20 m away from the tunnel face, the ground is uneven between 20 m and 30 m. Therefore, combined with the theoretical analysis and the actual situation, the two water bags were arranged 32 m and 35.5 m away from the tunnel face, respectively. The location of the water bag is shown in Fig. 5.

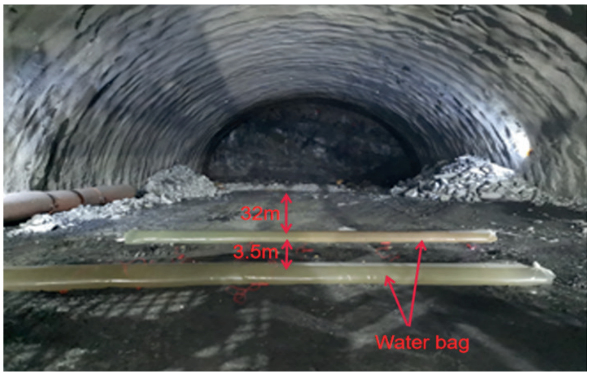


Fig. 5 Location of water bag on sit

In order to ensure that the water mist is evenly dispersed after blasting and effectively block blasting dust, 10 detonators and 300 g emulsion explosive are evenly spread under the two water bags. The layout parameters of the water bag and other blasting parameters used in this test as follows: the diameter of the water bag is 70 cm, the length of the water bag is 6 m, the spacing of the water bag is 3.5 m, the extension is 0.5 m, the number of detonators is ten, and the amount of explosives is 300 g.

(3) Location of measuring points

Considering the limited test equipment and test manpower, the dust concentration can be measured at the moment of blasting, it is necessary to place the equipment in the predetermined position, and worker must leave the site during blasting operation. Therefore, considering the rationality of the site and in order to protect the equipment from being smashed and safety, two dust monitoring systems were selected in this test. They are arranged at positions blasting A and B which are 40 m and 132.4 m away from the tunnel face, respectively. The measuring points were arranged as shown in Fig. 6.

4 Results and discussion

4.1 Numerical simulation results

4.1.1 Analysis of time difference between water bag initiation and tunnel face initiation

In order to explore the best capture effect of explosive water mist on dust, the detonation time of tunnel face and water bag were analyzed. By blasting dust transport can be seen the results of numerical simulation, the dust spread to 15 m takes about 2~5 s. Because of the dust before blasting spread to water bag over a period of time, the duration of the water mist in the air is only 5 s, and the time to reach the maximum spray height is only 1 s. So, it needs to set a certain initiation time difference.

To make the maximum atomization effect of the water mist catch the dust, the dust needs to reach the water bag before it blasting. Set the detonation time difference of 0.5 s, 1 s, 2 s and 3 s on the tunnel face and water bag and keep other parameters unchanged. The simulated effect of explosive water mist on dust removal is shown in Fig. 7.

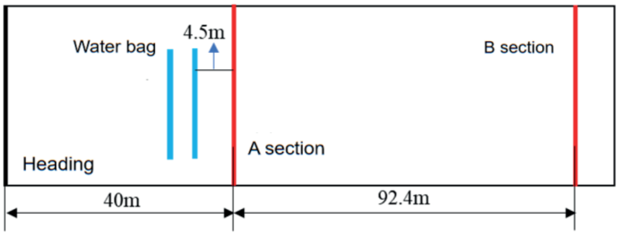


Fig. 6 Dust concentration measurement point layout with dust removal measures

It can be seen from Fig. 7 that:

(1) When the detonation time interval between the water bag and the tunnel face is 0.5 s, the dust has been diffused to the water bag and passed the water mist, so the water mist and the dust cannot be well combined to play the role of dust capture.

(2) When the detonation time interval is 1~2 s, the dust just moves to the position of the water bag, and the water mist has reached the maximum scattering height, which can intercept and capture the dust well.

(3) When the detonation time interval is 3 s, the dust does not spread to the position of the water bag. The water mist begins to fall down after being thrown to the highest position. The water mist cannot combine with the dust.

4.1.2 Analysis of the influence of explosive coefficient on atomization effect

The greater the concentration of water mist, the probability of collision with dust is greater, so as to combine with each other to achieve dust reduction. The amount of water in the water bag and the explosive are the direct factors that affect the concentration of explosive water mist. If the explosive coefficient K increases properly, the effect of blasting mist from the water bag is better.

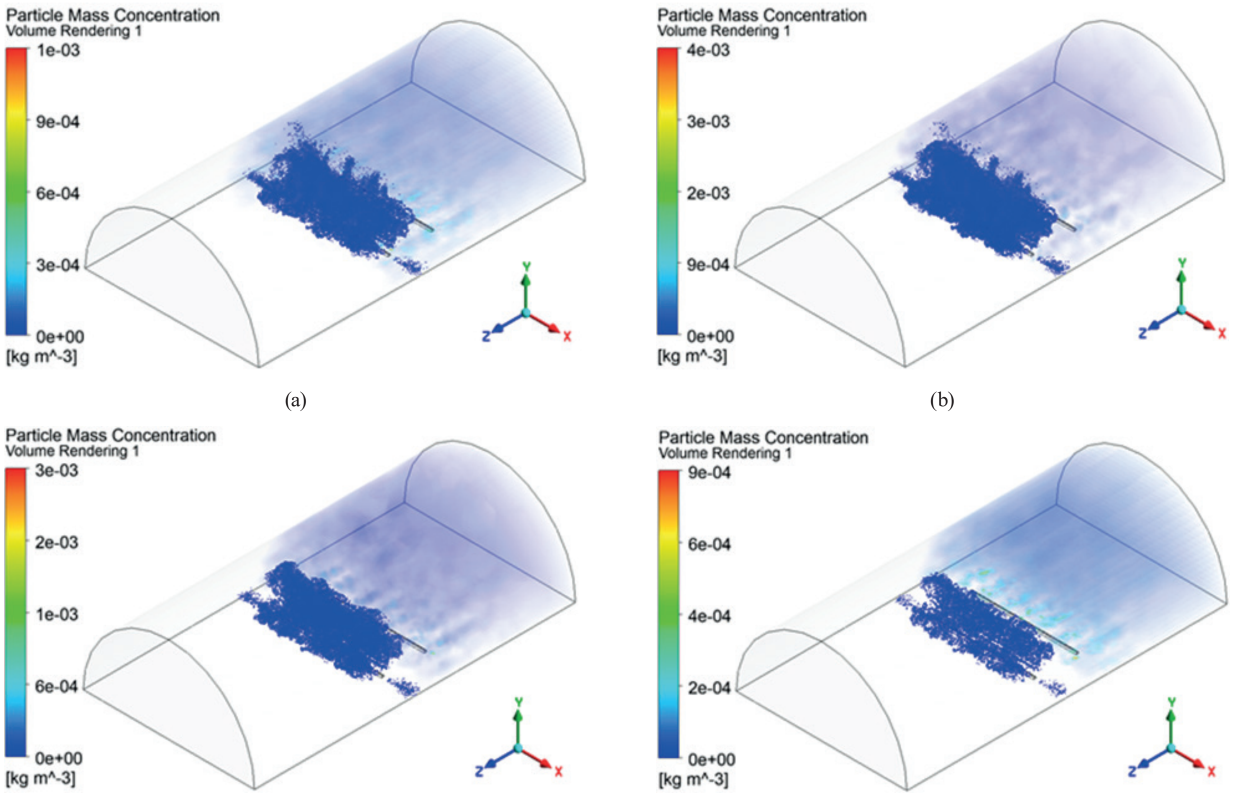
Therefore, the explosive coefficients of K = 0.3 g/L, 0.4 g/L, 0.5 g/L and 0.6 g/L are selected to simulate the atomization effect of water bag blasting with different explosive coefficients, which can also indirectly reflect the influence on the dust removal effect, as shown in Fig. 8.

As can be seen from the figure:

With the gradual increase of explosive coefficient K, the water mist formed by water bag blasting has a wider coverage area, a higher height, and a longer duration in the air, resulting in a more obvious atomization effect.

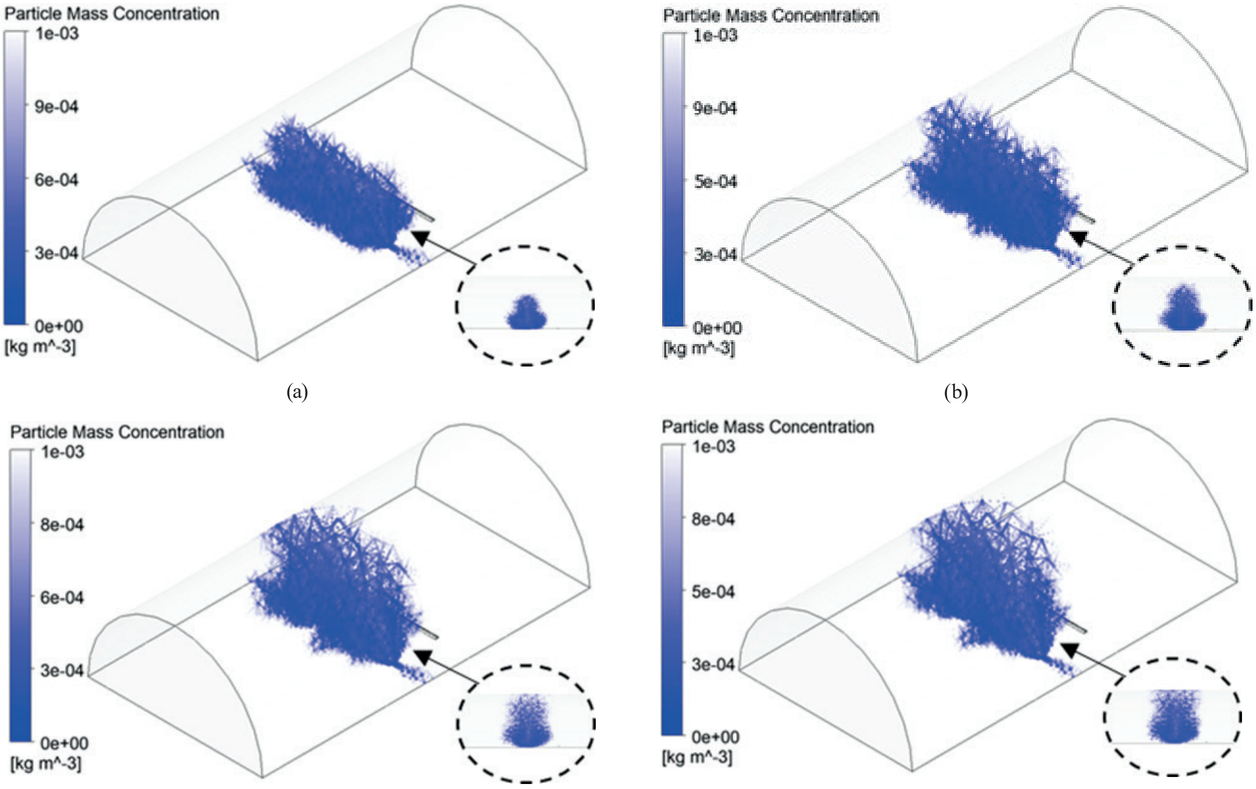
(2) When the explosive coefficient K = 0.3 g/L, the height of the water mist is only about 3 m, and the water mist cannot effectively intercept the dust in the upper part of the tunnel. When the explosive coefficient K = 0.4~0.5 g/L, the water mist can reach 6 m high, the coverage area is wider, so it is more suitable for dust removal; However, when the explosive coefficient K = 0.6 g/L, some droplets will wet the tunnel vault due to high dispersion, and the water consumption is relatively large.

Analyze the relationship between the height, width, coverage area and duration of water mist formed by blasting water bag and different explosive coefficients, as Fig. 9.



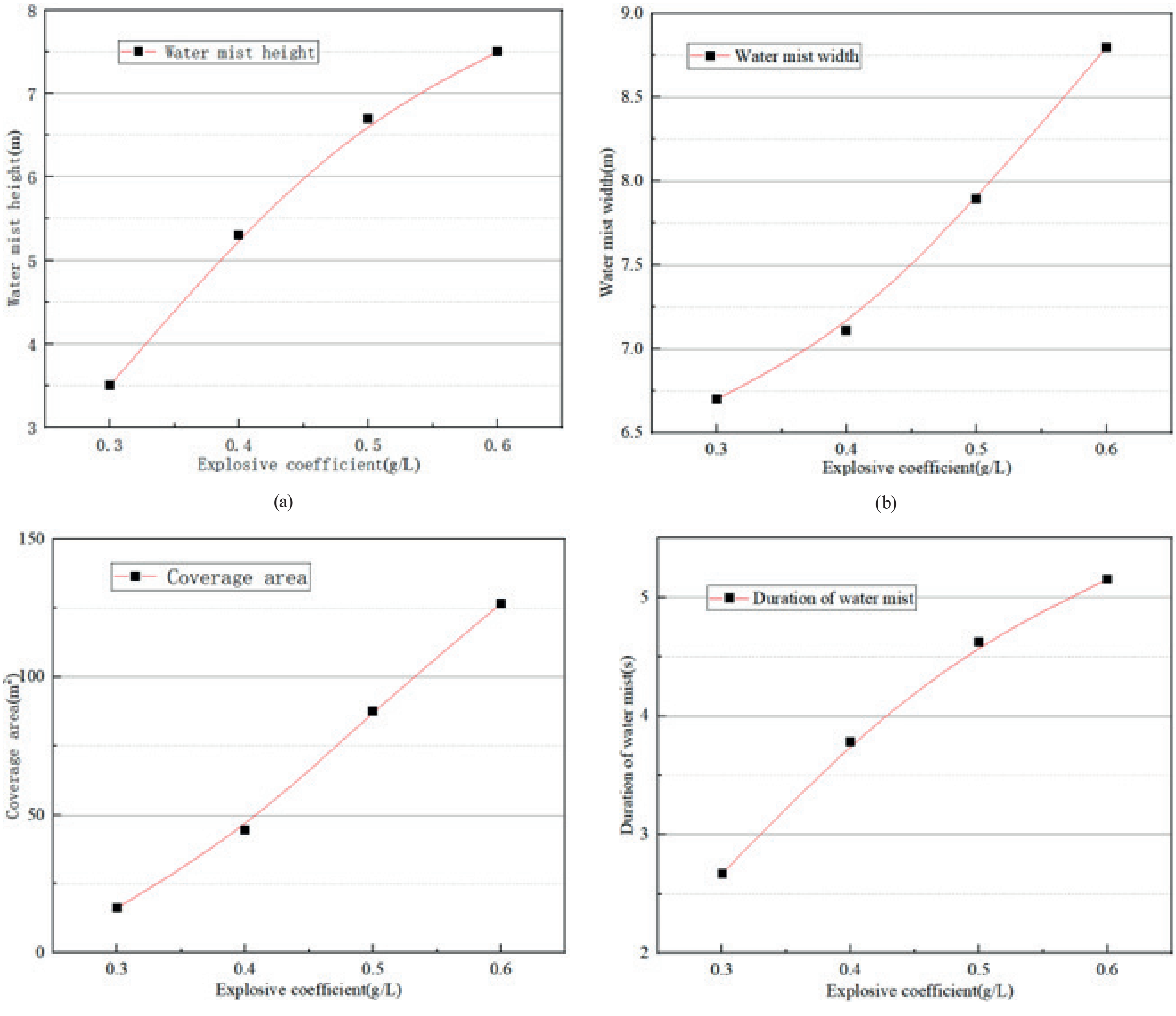
(a) (b) (c) (d)

Fig. 7 Influence of different initiation time intervals of water bag and tunnel face on dust removal effect; (a) Detonation at interval of 0.5 s, (b) Detonation at interval of 1 s, (c) Detonation at interval of 2 s, (d) Detonation at interval of 3 s



(a) (b) (c) (d)

Fig. 8 Atomization effect of water mist with different explosive coefficients; (a) K = 0.3 g/L, (b) K = 0.4 g/L, (c) K = 0.5 g/L, (d) K = 0.6 g/L



(a) (b) (c) (d)

Fig. 9 Duration of water mist under different explosive coefficients; (a) K = 0.3 g/L, (b) K = 0.4 g/L, (c) K = 0.5 g/L, (d) K = 0.6 g/L

As can be seen from the figure:

(1) Under the conditions of different explosive coefficients, the relationship between the increase and decrease of the height, width, coverage area and duration of water mist is basically consistent.

(2) With the increase of explosive coefficient, the height of water mist first increases rapidly, and then increases slowly. The main reason is that with the increase of the amount of explosive, it cannot obviously make the water spray higher, but will increase the lateral impact on the water bag and make the water droplets scatter around. Therefore, with the increase of explosive coefficient, the width of water mist increases slowly and then increases rapidly.

(3) The total coverage area of water mist is also affected by the height and width of water mist. As the length of the water bag is 10 m, when the explosive coefficient increases, the width of the water mist will also increase, and the overall coverage of the water mist will increase accordingly.

(4) The duration of water mist becomes longer with the increase of explosive coefficient, but there is no obvious duration effect after reaching a certain value. This is because the larger the explosive coefficient is, the greater the force on the water bag will be. The droplet group is more likely to be broken twice to form water mist, while the water mist will fall back and settle relatively slowly, and the attenuation time will be longer.

4.1.3 Analysis of influence of water bag spacing on dust removal effect

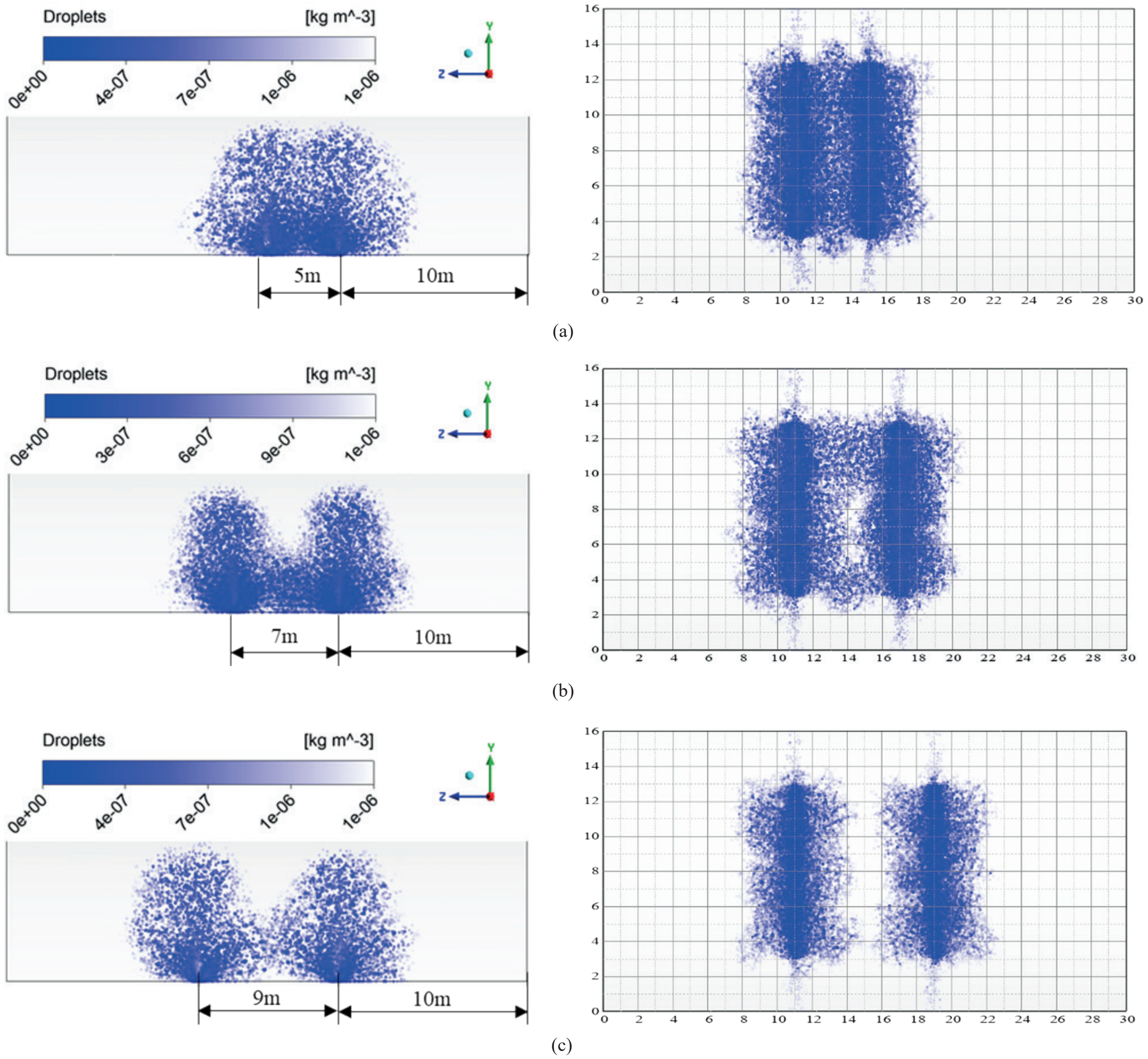
The distance between water bags is also an important parameter affecting the dust removal effect of explosive water mist. The distance between water bags directly affects the overlapping coverage area of explosive water mist, as well as the duration of water mist, thus affecting the dust removal efficiency. In order to analyze the

influence of different spacing between water bags on the dust removal effect, the simulated atomization effect of water bag blasting at different spacing is shown on the left side of Fig. 10. Grid method is used to divide the top view of water bag blasting at 1s after different spacing, as shown on the right side of Fig. 10.

In order to further analyze the blasting effect of water bag and measure the blasting rate of water bag, the height of water bag blasting, the width of water bag blasting, and the covered area of water spray are taken as the important factors. By reading the grid scale as an approximation of the actual height and an approximation of the width, the records are shown in Table 7.

Table 7 Indicators of mist at 1s with different spacing

Heating pad spacing	Water spray height (m)	Water mist width (m)	Area covered by water mist (m^2)
5 m	7.5	9	90
7 m	7	11.5	115
9 m	7	10	100



(a)

(b)

(c)

Fig. 10 Atomization effect of explosive water mist at different water bag spacing; (a) The interval is 5 m, (b) The interval is 7 m, (c) The interval is 9 m

It can be seen from Fig. 10 and Table 7 that:

(1) The larger the distance between the water bags, the smaller overlapping area of the explosive water mist between the two water bags and the larger the overall coverage area. Meanwhile, the distance between the water bags will also affect the spraying width of the water mist.

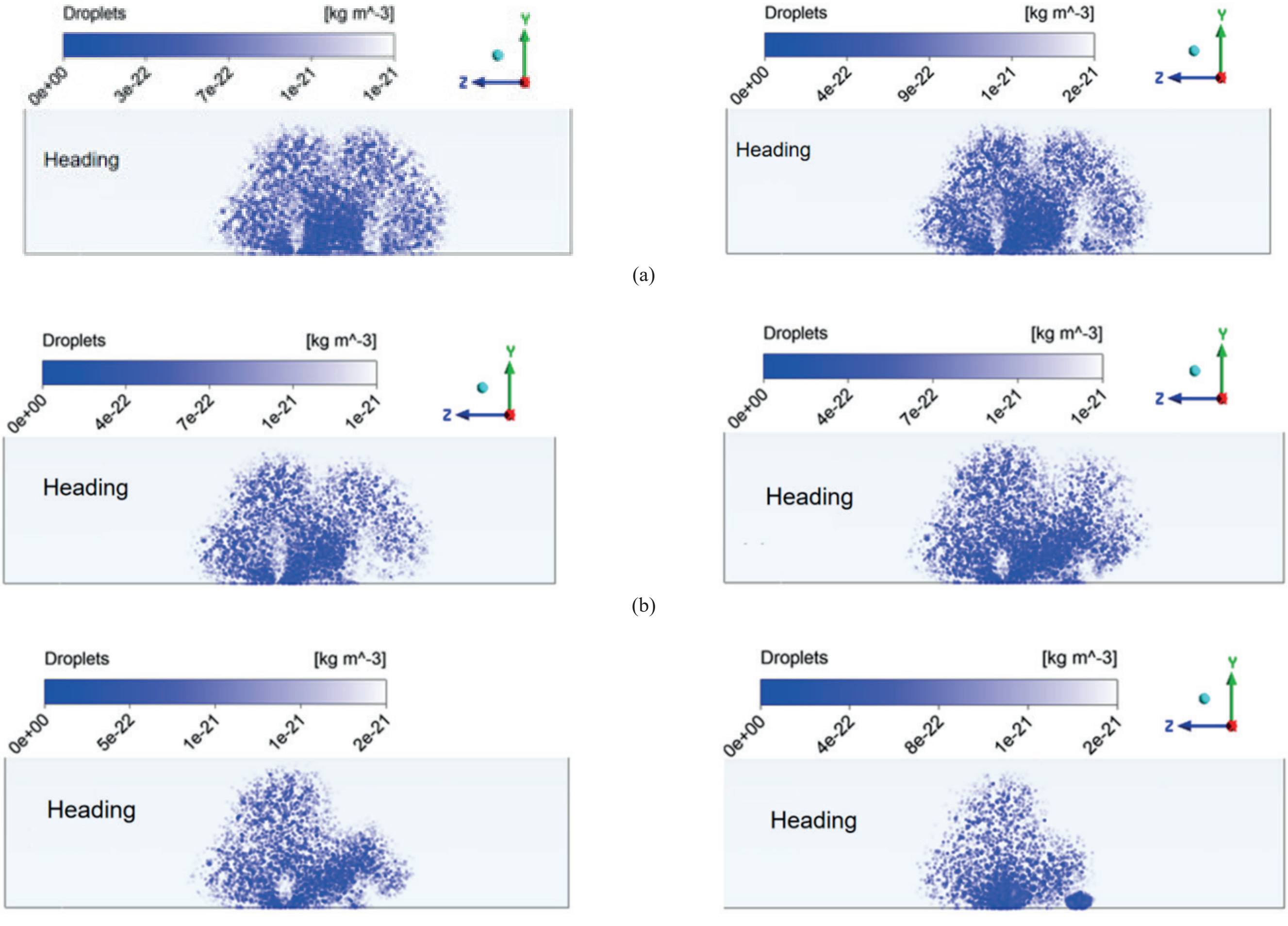
(2) When the space between water bags is 5~7 m, the overlap area of water mist is larger. The overall coverage area can reach 115 m^2, which indicates that the concentration of water mist per unit volume is larger. There are more droplets in the water mist field, which can increase the probability of collision and combination of water mist and dust, thus improving the dust removal rate.

(3) When the distance between the water bags was 7~9 m, the cross rate of water mist between the two water bags is low, but the overall coverage area does not increase. After achieving the maximum atomization effect, the water mist will dissipate faster.

To sum up, in order to achieve the maximum atomization effect during water bag blasting and achieve the maximum dust removal rate, the time difference between the water bag and the tunnel face should be set as 1~2 s, the explosive coefficient is 0.6 g/L, and the distance between water bag is 5~7 m.

4.1.4 Analysis of detonation time difference between water bags

Due to the different initiation time, the water mist effect presented by the two water bags is often different, and the dust capture efficiency will be different. In order to analyze the influence of initiation time difference between water bags on atomization effect of water bags, the atomization effect is better when the space between water bags is 7 m, and the space is moderate. Therefore, the atomization effect with different time difference when the space between two water bags is 7 m is simulated, and the results are shown in Fig. 11.



(a)

(b)

(c)

Fig. 11 Atomization effect of two water bags with different initiation time difference; (a) Detonation at 0 s interval, (b) Detonation at 0.2 s interval, (c) Detonation at 0.5 s interval, (d) Detonation at 1 s interval, (e) Detonation at 1.5 s interval, (f) Detonation at 2 s interval

Among them, the first water bag close to the tunnel face is set to detonate first, and the second water bag is set to detonate later. The detonation time interval of the two water bags is set to be 0 s, 0.2 s, 0.5 s, 1 s, 1.5 s, 2 s, respectively. As can be seen from Fig. 11:

(1) When the detonation interval of two water bags is 0~0.5 s, the overall atomization effect of water bag blasting is better. When the first water bag reached the highest point, the second water bag also reached the highest point. Mist drops are relatively dense, and the two water bags can be used as a barrier to effectively intercept dust.

(2) When the interval is 1~1.5 s, the water mist of the first water bag reaches the highest point, but the spraying of the second water bag has not reached the maximum atomization effect; When the interval is 2 s, the mist drops of the first water bag have started to fall from the peak, while the second water bag just burst and began to disperse.

(3) When the detonation time interval of two water bags is too large, the two cannot achieve the maximum atomization effect and cannot be a barrier to each other, the best dust catching effect cannot be achieved. Therefore, in practical application, it is more appropriate to set the detonation time difference of water bag to 0~0.5 s.

Water mist concentration is an important index to measure the atomization effect of explosive water mist. For this purpose, five monitoring points (z1 = 0 m, z2 = 1 m, z3 = 2 m, z4 = 3 m, and z5 = 4 m) are set to monitor the water mist concentration of two water bags at different time intervals, as shown in Fig. 12.

As can be seen from Fig. 12, different initiation times of two water bags will affect the overall water mist concentration. The longer the blasting interval between two water bags, the lower the concentration of water mist formed by blasting. When two water bags are detonated at the same time, the highest concentration of water mist is 0.00283 kg/m^3. At the same time, the farther away from the water bag, the lower the concentration of water mist. Therefore, the detonation time interval between water bags also has a certain influence on the dust removal efficiency.

Above all, to achieve the best effect of dust, preliminarily determines the water bag in blasting, the key parameters of constraints when water bag and the initiation of jet lag is set to 1~2 s, explosive coefficient is 0.6 g/L, water bag spacing is 5~7 m, firing interval of 0~0.5 s between water bag, water bag layout constraints from 15 to 30 m, water bag explosion optimal atomizing effect.

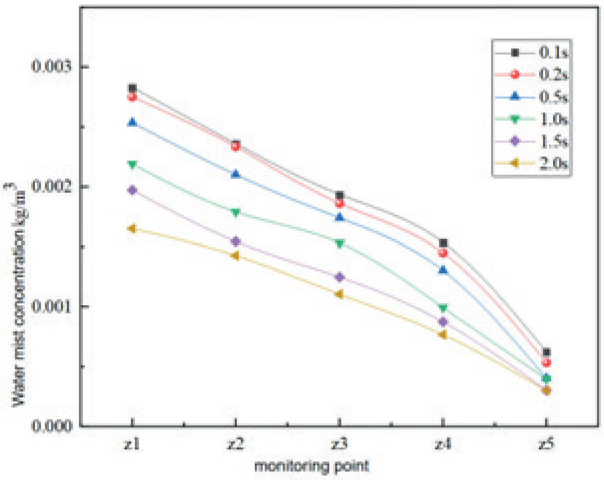


Fig. 12 Water mist concentration at each monitoring point during detonation of two water bags at different time intervals

4.2 Field test results

The dust concentration with and without explosive water mist dust removal measures is measured, and the data statistics are shown in Table 8. Compare and analyze the dust concentration values of section A and section B within 15 min before and after blasting, and draw the curve with Origin, as shown in Fig. 13.

After blasting, the dust concentration in section A and B increases rapidly at first, then decreases slowly and finally remains stable. The dust concentration of section A and B reach the maximum in about 3 minutes, which are 32.532 mg/m^3 and 15.374 mg/m^3, respectively. With the passage of time, the dust concentration of section A and B is stable at about 3 mg/m^3, which is because the air in the tunnel will be disturbed during the shoveling and transportation process, and the dust is not easy to settle.

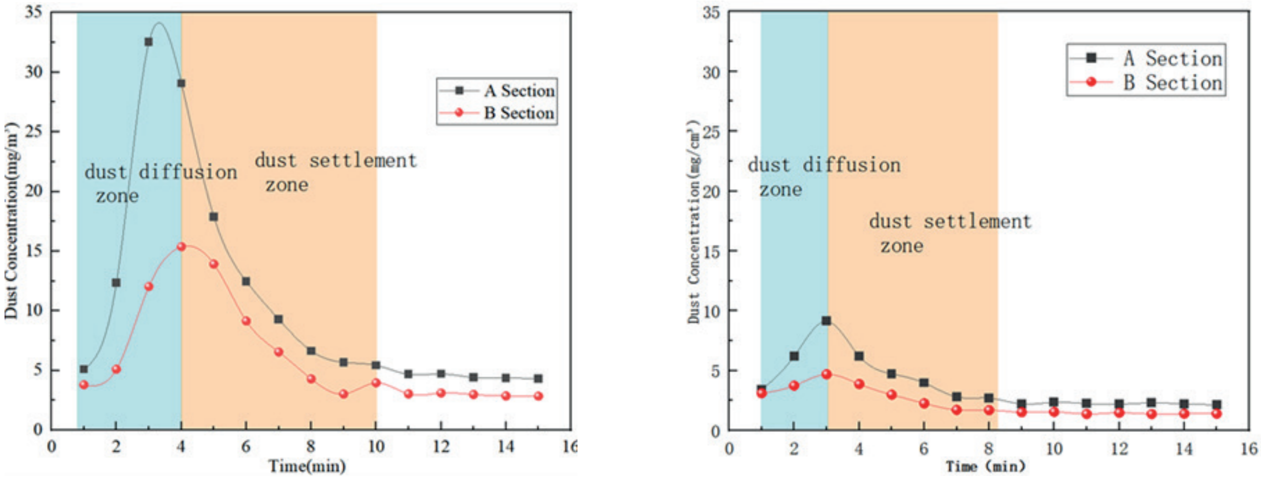
The comparison of dust concentration before and after blasting shows that the blasting operation will make the dust concentration in the tunnel increase sharply, and it is not easy to settle. At the same time, the closer to the tunnel face, the higher the dust concentration, and the dust concentration decreases slowly with the passage of time. In the absence of dust removal measures, the peak dust concentration is high, and the attenuation time is slow, which will pollute the working environment for a long time.

After blasting, the dust concentration of section A and B both reach the peak in about 3 minutes, respectively 13.512 mg/m^3 and 6.107 mg/m^3. Thereafter, the dust concentration of the two sections decreased rapidly to stability.

After blasting, the initial concentration of section A and B is relatively high, on the one hand, the small particles of dust originally suspend in the tunnel does not settle; On the

Table 8 Dust concentration in 15 min before and after blasting with or without dust removal measures

Monitoring the time	Without measures(mg/m^3)		Monitoring the time	With measures(mg/m^3)	
	A section	B section		A section	B section
14:44	5.091	3.798	12:24	3.932	3.467
14:45	12.344	5.099	12:25	8.650	4.582
14:46	32.532	12.037	12:26	13.512	6.107
14:47	29.071	15.374	12:27	8.664	4.783
14:48	17.865	13.915	12:28	6.175	3.345
14:49	12.458	9.145	12:29	4.920	2.105
14:50	9.285	6.544	12:30	3.028	1.253
14:51	6.637	4.287	12:31	2.785	1.156
14:52	5.675	3.016	12:32	2.013	0.884
14:53	5.423	3.963	12:33	2.274	0.892
14:54	4.671	3.029	12:34	2.115	0.658
14:55	4.701	3.112	12:35	1.918	0.773
14:56	4.408	2.982	12:36	2.064	0.639
14:57	4.357	2.858	12:37	1.996	0.687
14:58	4.306	2.843	12:38	1.907	0.643



(a)

(b)

Fig. 13 Dust concentration curve within 15 min after blasting; (a) Without measures, (b) With measures

other hand, the explosion water mist has not fully captured the dust sprayed from the tunnel face. Some dust escaped from both sides of the water bag, resulting in an instant increase in concentration.

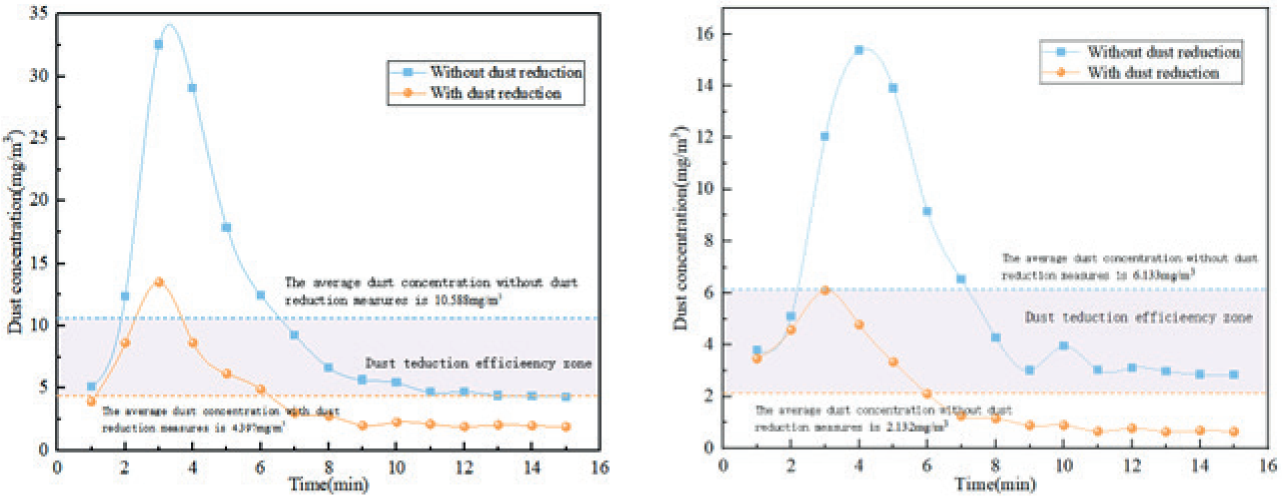
Taking two sections A and B as the analysis objects, the change rule of dust concentration with time is compared and analyzed without dust removal measures and with dust removal measures. Import the data into Origin to draw the dust concentration curves of sections A and B with or without dust reduction measures, as shown in Fig. 14.

The dust removal efficiency of the two sections over time is shown in Fig. 15.

It can be seen from Figs. 14 and 15 that:

(1) Regardless of whether the dust removal measures of explosive water mist are taken, the dust concentration of section A and B will gradually increase over time and then decrease. The main reason is that the amount of dust produced by tunnel blasting is large, it takes a certain time for the dust to spread to the measuring point. Under the condition of no dust removal measures, the average dust concentration of section A and Section B is 6.191 mg/m^3 and 4.001 mg/m^3 higher than that with dust removal measures.

(2) Under the condition of explosive water mist dust removal measures, the dust concentration of section A and B reaches the peak first and then decays rapidly compared with that without dust removal measures, the dust



(a) (b)

Fig. 14 A and B sections with or without dust reduction dust concentration comparison; (a) A section, (b) B section

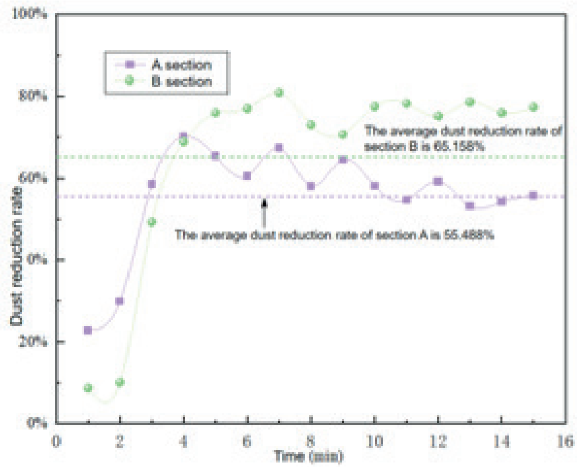


Fig. 15 Dust removal efficiency in sections A and B

concentration of both sections stabilizes. This indicates that the explosion spray effectively captured the dust, making the dust floating in the tunnel for a short time.

(3) The maximum dust removal rate of section A is 70.20% and B is 80.85%, the average dust removal rate of section A and B is 55.49% and 65.16%, respectively. In the first 6 minutes, the dust removal rates of both sections showed an increasing trend, which is due to the increasing effective collision rate between water mist and dust. Since then, the dust removal rate of Section B is higher than that of section A, because the dust settle, or is captured before reaching Section B, and it cannot be ruled out that the interaction between water mist and dust is still continuing.

4.3 Summary

The numerical simulation analysis is carried out on four factors including initiation time difference between water bag and tunnel surface, explosive coefficient, distance between water bag and initiation time difference between water bags, so as to obtain the parameter setting of the best dust removal effect of water mist. Then, field test is carried out to verify the gap between the dust removal measures with water mist and those without water mist.

According to the simulation results, the reasonable parameters are as follows: when the detonation time difference is set as 1~2 s, the explosive coefficient is 0.6g/L, the distance between water bags is 5~7 m, the detonation interval between water bags is 0~0.5 s, and the water bag is arranged 15~30 m away from the face of the palm. The field experiment is designed according to the parameter range obtained by the numerical simulation. The parameters range obtained according to the numerical simulation results can achieve better dust removal effect. The numerical simulation has certain guiding significance for water mist dust removal. If water mist dust removal is set, more than 60% dust removal rate can be achieved, and the dust removal effect is relatively obvious, which greatly reduces the ventilation time after blasting and has relatively high promotion value.

5 Conclusions

In this paper, the method of using water mist to reduce dust in the tunnel constructed by drilling and blasting method is proposed, and the mechanism of explosion water mist dust reduction is studied by laying water bags in front of the tunnel face to reduce dust by explosion, at the same time, the factors affecting the explosion water mist are analyzed by using fluent software, finally the feasibility of theoretical analysis and numerical simulation results is verified by combining engineering examples, the following conclusions are mainly obtained:

(1) Droplets atomization is roughly divided into two stages, the first crushing stage and the second crushing stage. When the viscosity of droplets is small and the resistance and surface tension are the same, the second crushing into mist is more likely to occur.

(2) When the explosive coefficient is 0.45~0.55 g/L, the larger the ratio of length to diameter of the water bag is, the surface activity of water is 5 kg/m^3. When the water bag is arranged 15~30 m away from the tunnel face, the mist explosion effect of the water bag is the best.

(3) In order to achieve the best dust removal effect, the key parameters of explosive water mist dust removal obtained by numerical simulation are as follows: the detonation time difference between water bag and tunnel face is set as 1~2 s; The explosive coefficient is 0.6 g/L; Water bag spacing is 5~7 m; The detonation interval between water bags is 0~0.5 s.

(4) Through the field test, the average dust removal rate of the section with explosive water mist dust removal technology can reach more than 60%, the dust removal effect is relatively obvious. It proves that this technology is very suitable for the dust removal of the tunnel construction by drilling and blasting method and has a high promotion and application value.

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References

[1] Wallace, K. A., Cheung, W. M. "Development of a compact excavator mounted dust suppression system", Journal of Cleaner Production, 54, pp. 344–352, 2013. https://doi.org/10.1016/j.jclepro.2013.04.048

[2] Li, X. "Experimental study on Dust removal Mechanism of Explosive water mist", MSc Thesis, Anhui University of Science and Technology, 2005.(in Chinese) https://doi.org/10.7666/d.y776775

[3] Han, Z., Hu, B., Yan, S. "Application of Explosive water mist to dust removal in urban Demolition blasting", Coal Mine Blasting, 4, pp. 30–32, 2008. (in Chinese)

[4] Li, W., Zhang, X., Ke, S., Meng, Y., Liu, G. "Research on application of dust removal technology by blasting in open-pit limestone mine", Engineering Blasting, 24(5), pp. 72–77, 2018. (in Chinese) https://doi.org/10.3969/j.issn.1006-7051.2018.05.012

[5] Zhang, Z., Tong, Y., Li, Z., Bai, H., Liu, J. "Experimental study on dust removal by water mist in step blasting in open-pit mine", Engineering Blasting, 23(5) pp. 71–75, 2017. (in Chinese) https://doi.org/10.3969/j.issn.1006-7051.2017.05.014

[6] Yang, N., Guo, Y., Bai, H., Zhang, Z. "Experimental study on dust suppression of open pit blasting by explosive water spray", Blasting, 38(3), pp. 130–135, 2021. (in Chinese) https://doi.org/10.3963/j.issn.1001-487X.2021.03.020

[7] Guo, Y. "Quantification and visualization of Blasting dust based on Gaussian Diffusion model", Journal of the China Railway Society, 44(1), pp.153–159, 2022. (in Chinese) https://doi.org/10.3969/j.issn.1001-8360.2022.01.020

[8] Wu, J., Han, Q. "Theory, Method and Application of Computational Fluid Dynamics" Science Press, 1988. ISBN 703000275X (in Chinese)

[9] Fletcher, D. F. "Computational techniques for fluid dynamics", [Book review] Scientific Computation, 70(1), p. 221, 2014. https://doi.org/10.1016/0010-4655(92)90103-6

[10] Toraño, J., Torno, S., Menéndez, M., Gent, M. "Auxiliary ventilation in mining roadways driven with roadheaders: Validated CFD modelling of dust behaviour", Tunnelling and underground space technology, 26(1), pp. 201–210, 2011. https://doi.org/10.1016/j.tust.2010.07.005

[11] Lu, Y., Akhtar, S., Sasmito, A. P., Kurnia, J. C. "Prediction of air flow, methane, and coal dust dispersion in a room and pillar mining face", International Journal of Mining Science and Technology, 27(4), pp. 657–662, 2017. https://doi.org/10.1016/j.ijmst.2017.05.019

[12] Guo, C., Nie, W., Xu, C., Peng, H., Zhang, C., …, Li, M. "A study of the spray atomization and suppression of tunnel dust pollution based on a CFD-based simulation", Journal of Cleaner Production, 276, 123632, 2020. https://doi.org/10.1016/j.jclepro.2020.123632

[13] Deng, X., Liu, Z., Liu, Z. "Three-dimensional Numerical Simulation of Ventilation in single-head Tunneling and press-in Construction of Lianghekou Long Tunnel", Journal of Civil and Environmental Engineering, 36(2), pp. 35–41, 2014. (in Chinese) https://doi.org/10.11835/j.issn.1674-4764.2014.02.006

[14] Zhang, L., Zhou, G., Ma, Y., Jing, B., Sun, B., Han, F., He, M., Chen, X. "Numerical analysis on spatial distribution for concentration and particle size of particulate pollutants in dust environment at fully mechanized coal mining face", Powder Technology, 383, pp. 143–158, 2021. https://doi.org/10.1016/j.powtec.2021.01.039

[15] Feng, Z. "Study on dust migration law and spray dust removal technology of Fully mechanized Mining face", MSc Theis, Xi 'an University of Science and Technology, 2019. (in Chinese)

[16] Jiang, Z., Wang, Y., Men, L. "Ventilation control of tunnel drilling dust based on numerical simulation", Journal of Central South University, 28(5), pp. 1342–1356, 2021. https://doi.org/10.1007/s11771-021-4704-z

[17] Samirant, M., Smeets, G., Baras, C., Royer, H., Oudin, L. R. "Dynamic Measurements in Combustible and Detonable Aerosols", Propellants, Explosives, Pyrotechnics, 14(2), pp. 47–56, 1989. https://doi.org/10.1002/prep.19890140203

[18] Faeth, G. M., Hsiang, L.-P., Wu, P.-K. "Structure and breakup properties of sprays", International Journal of Multiphase Flow, 21, pp. 99–127, 1995. https://doi.org/10.1016/0301-9322(95)00059-7

[19] Zhang, Y. S. "Numerical Simulation of Droplet Secondary Atomization Breaking Mode", MSc Thesis, Shanghai Jiao Tong University, 2015. (in Chinese) https://doi.org/10.15959/j.cnki.0254-0053.2015.04.003

[20] Guan, R., Meng, H., Xue, L., Kang, Y. "Experimental Study on Blasting Dust capture and Adsorption Technology", Railway Construction, 2017(1), pp. 68–71, 2017. https://doi.org/10.3969/j.issn.1003-1995.2017.01.15

[21] Liu, F., Yan, S., Yue, Z. "Effect of Length to Diameter ratio of exploding water bag on Motion Characteristics of Water Explosion Spray", Pyrotechnics, 2008(2), pp. 34–37, 2008. https://doi.org/10.3969/j.issn.1003-1480.2008.02.010

[22] Liang, R. "Rock Throwing Velocity of Blasting", Engineering Journal of Wuhan University, 1980(3), pp. 39–46, 1980. (in Chinese)

[23] Ma, L., Li, K., Ding, X., Xiao, S., Liu, G., Zhang, C. "Research on Influencing factors of projectile distance of rock mass in projectile blasting", Engineering Blasting, 19(1), pp. 50–53, 2013. (in Chinese) https://doi.org/10.3969/j.issn.1006-7051.2013.01-02.012

[24] Wu, W. "Dynamic Analysis of Partition Wall in Multi-arch Tunnel under Blasting Flying Stones", MSc Thesis, Changsha University of Science and Technology, 2013. (in Chinese) https://doi.org/10.7666/d.Y2306608