Atomization performance of Tiantaishan tunnel spray dust reduction

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Abstract. In order to further improve the efficiency of spray dust removal in tunnel and obtain favorable equipment parameters, the dust removal performance of high pressure spray atomization particle size was deeply studied. Taking the dust generated in Tiantai Mountain tunnel as the research object and combining with the numerical simulation method, based on FLUENT pressure-swirl atomization model, in this paper, the mechanism of high pressure spray dust reduction is analyzed. The pressure nozzle is simulated at 4 pressures (2, 3, 4, 5 Mpa) and 3 nozzles (2.0, 1.5, 1.0 mm in diameter). The simulation results show that when the nozzle diameter is constant, the droplet size decreases with the increase of pressure, and the atomization effect is better. When the spray pressure is constant, the droplet size increases with the increase of nozzle diameter. According to the measured results of dust in Tiantai Mountains, it is suggested that the nozzle diameter should be 1.5 mm and the working pressure should be 4 Mpa, which can reasonably and effectively settle the fine particles of dust in the tunnel.

1. Introduction
At present, the main dust control measures adopted in tunnel construction in China are spray dust reduction, ventilation dust reduction, dust capture by dust remover and water curtain dust reduction. Spray dust control has been widely used because of its advantages of economy, simplicity, practicality and good effect in dust control. However, from the practical application of tunnel construction, spray dust control still has not achieved the desired effect [¹]. In other industries, such as internal combustion engine, high pressure atomization, industrial atomization drying, wetting and reaction, The atomization mechanism, such as droplet atomization jet breakup, film breakup, laser holography, high-speed photography and laser Doppler method for atomization particle size measurement, are put forward, which lays a theoretical and experimental foundation for the application of nozzles in these industries [²,³]. For spray dust reduction during tunnel construction, it is necessary to make further research and discussion on tunnel spray theory, that is, the interaction between spray pressure, water mist particle size and dust particle size, etc. to improve the effect of spray dust reduction.
2. Relationship between spray granularity and dust granularity
Spray dust reduction is the process of colliding and condensing and settling between liquid fog particles and solid dust particles, and its main mechanisms include inertial collision, interception, diffusion, gravity effect, electrostatic effect and vortex condensation\cite{4}.

The spray characteristics of nozzle mainly include droplet size, distribution density, moving speed, effective range, structure of spray body, charge property, and residence time of droplet in air, etc. \cite{5-7}. In the process of tunnel construction, the main influencing factors of spray characteristics are nozzle diameter and spray pressure\cite{8}.

Xie Yaoshi\cite{1}, Liu Xiangsheng\cite{9}, etc., through theoretical and experimental research, obtained the minimum particle size relationship of spray mist drops to catch dust, which is:

\[ d_{\text{pmin}} = \sqrt{\frac{9 \mu S_{tk}}{\rho_p v_0}} \]  

Type: \( d_{\text{pmin}} \), dust particle size, m; \( S_{tk} \), the inertial collision coefficient; \( \mu \), the aerodynamic viscosity, Pa/s, take 1.8 ×10^-5 Pa/s; \( D \), the particle size of the fog droplets, m; \( \rho_p \), the dust density, kg/m^3; \( v_0 \), the flow field speed, m/s.

In the formula, the spray particle size can be determined by simulation under the condition that the nozzle form and spray pressure are constant and dust concentration and air flow velocity can be measured. As can be seen from the formula (1), the droplet size is proportional to the minimum dust size that can be trapped, and therefore, the droplet size must be small in order to trap respirable dust having a very small particle size. Increasing the spray pressure can improve the atomization degree, but under a certain spray flow rate, if the spray pressure is too high, the droplet size will be too small, the retention time in the air will be very short, and the dust removal effect will also be affected \cite{10}.

3. Numerical simulation of Spray particle size
3.1. Model and boundary conditions
The simulation of spray field is based on Fluent's pressure-swirl atomization model, which simulates the law of water atomized into the tunnel under different nozzle diameters and spray pressures. The spray pressure was 2, 3, 4 and 5 Mpa, and the nozzle diameters were 1.0, 1.5 and 2.0 mm. In order to save the simulation cost, the simplified model size is 1m × 1m × 5m, and the mesh size is 0.1. The boundary parameters of the spray are set as shown in Table 1.

| items                      | boundary parameters                  |
|----------------------------|--------------------------------------|
| Broken model               | pressure-swirl-atomizer              |
| Nozzle diameter (mm)       | 1.0, 1.5, 2.0                        |
| Spray pressure (Mpa)       | 2, 3, 4, 5                           |
| Position                   | (0.5, 0.5, 0)                        |
| Injection direction        | z                                    |
| Injection half-angle       | 30                                   |

3.2. Analysis of simulation results
The particle size distribution can be obtained by turning on particle trajectory tracking. Because of many simulation results and the same data rule, only the droplet size distribution under different pressures at 1.5 mm nozzle diameter and different nozzle diameters at 3Mpa were analyzed as examples. Because of the large amount of data, the size of the atomized dropsize distribution is described by \( d \) (0.1), \( d \) (0.5), \( d \) (0.5), \( d \) (0.5) is the particle-accumulated particle distribution of 50%. Figure 1 shows the distribution of the particle size of the fog droplets at each pressure at a nozzle diameter of 1.5mm.
As can be seen from Figure 1, the droplet size gradually decreases with increasing pressure, and the minimum droplet size is 90.9 μm at 2 Mpa, 59.5 μm at 3 Mpa, 43.7 μm at 4 Mpa, and 33.3 μm at 5 Mpa. When the spray pressure is 3 MPa, the atomized droplet size is nearly 30% smaller than that of 2 MPa, and the atomization effect is obviously better.

As can be seen from Figure 2, with the increase of nozzle diameter, the particle size of the atomized droplets is gradually increased, and when the spray pressure is 3Mpa, the nozzle atomized droplet with a diameter of 1.0mm has a minimum particle size of 28.3μm, the nozzle atomized droplet with a diameter of 1.5mm has a minimum particle size of 59.5μm, and the nozzle atomized droplet with a diameter of 2.0mm has a minimum particle size of 59.7μm. Nozzles with a diameter of 1.5mm have a similar atomization effect to 2.0mm nozzles.

4. Tiantaishan Tunnel spray dust reduction analysis
The Tiantai Mountain Tunnel is a control project of Baoji-Pingkan Expressway. The dust control measures in tunnel construction are very important and necessary. Measure the wind speed of the tunnel flow field and sample the dust generated in each construction process in the 10th bid section of Tiantai Mountain Tunnel. Figure 3 shows the field test. The particle size of the dust was measured with a laser particle size distributor, and the particle size distribution of the dust in each construction process was analyzed as shown in Table 2.
Figure 3. Dust field test

Table 2. Tiantaishan Tunnel construction dust particle size distribution table

| Particle size /μm | Construction process |
|-------------------|----------------------|
|                   | Blasting of right line | Slag of right line | Spray of right line | Left-line blasting | Slag of left line | Spray of left line |
| d (0.1)           | 4.697                | 3.556              | 4.650              | 3.798              | 4.650            | 5.329             |
| d (0.5)           | 624.568              | 203.394            | 291.269            | 90.216             | 380.080          | 474.756           |
| d (0.9)           | 1356.987             | 1077.113           | 956.1140           | 776.215            | 1190.347         | 1166.527          |

As can be seen from the data in Table 2, the distribution of the respirable dust (particle size ≤ 5 μm) generated in each process is basically the same, and the proportion of the respirable dust is basically above 10%. In order to meet the requirement of settling this part of the small particle size dust, it is necessary to adopt a spray with a smaller particle size. Taking the right-line slag discharging operation as an example. Figure 4 is the dust particle size distribution diagram when the right line slag.

Figure 4. Particle size map of slag dust out of the right line

From the analysis of FIG. 4, it can be seen that among the components of the inhalable dust (particle size ≤ 15 μm), the dust particles with the largest percentage of particle size are 4-10 μm, followed by 1-4 μm dust particles. Large particles with particle size greater than 100 μm also account for a large proportion, but such large particles can settle naturally quickly and do not require high spray atomization requirements. Some studies [11] suggest that the dust collection efficiency of water mist is related to the relative particle size of dust and water mist. When the particle size of water mist is 100 ~ 150 times of the particle size of dust, the dust removal effect is better. Therefore, the particle size of water mist should be about 200 μm in order to settle the dust below 2 μm.
When selecting the nozzle, considering that the effective residence time of the droplets in the air can not be too short and the excessive spray pressure will increase the wear of the equipment, the nozzle diameter of 1.5 mm and the working pressure of 4 Mpa can meet the requirements. FIG. 5 is a graph showing the results of numerical simulation of atomized droplet size when nozzle parameters are 1.5 mm and 4 Mpa. From the analysis of FIG. 5, when nozzle diameter is 1.5 mm and working pressure is 4 Mpa, the minimum atomized droplet size is 43.7 μm, and the atomized droplet size is mainly distributed in the range of 120 μm ~ 210 μm, which can meet the requirements of dust reduction.

5. Conclusions and discussions

(1) Based on the analysis of the mechanism of high pressure spraying, the relationship between the droplet size and the dust size is obtained through the study of the performance of high pressure spraying, that is, the droplet size is proportional to the minimum dust size that can be trapped by the droplet.

(2) The results of numerical simulation show that the droplet size decreases with the increase of pressure and the atomization effect is better when the nozzle diameter is constant. When the spray pressure is constant, the droplet size increases with the increase of nozzle diameter. The smaller the droplet size, the shorter the droplet residence time in the environment.

(3) The distribution of respirable dust (particle size ≤ 5 μm) produced in each process of Tiantai Mountain Tunnel construction is basically the same, and the proportion of respirable dust is basically above 10%.

(4) According to the results of the dust measurement in Tiantaishan, it is suggested that the nozzle diameter should be 1.5 mm and the working pressure should be 4 Mpa, which can reasonably and effectively settle the fine particles of dust in the tunnel.

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