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Dust removal efficiency of high pressure atomization in underground coal mine

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ABSTRACT

To master theoretical calculation for dust removal efficiency of high pressure atomization in an underground coal mine, the corresponding atomization characteristics and dust removal efficiency were both comprehensively studied in theory by virtue of related theories of hydromechanics and aerosol. According to actual measurements of flow coefficients and atomization angles of X-type swirl nozzle, computational formula was derived for atomized particle sizes of such a nozzle in conjunction with relevant empirical equation. Moreover, a mathematical model for applying high pressure atomization to dust removal in underground coal mine was also established to deduce theoretical computation formula of fractional efficiency. Then, Matlab was adopted to portray the relation curve between fractional efficiency and influence factors. In addition, a theoretical formula was also set up for removal efficiency of respirable dust and total coal dust based on dust size and frequency distribution equations. In the end, impacts of dust characteristic parameters on various dust removal efficiencies were analyzed.

1. Introduction

Various links of production in underground mine can generate dusts in different extents. Dust suspended in air not only jeopardizes health of workers, but gives rise to bad influences on underground safety production. At present, measures such as dust removal by ventilation, water pre-infusion for coal mass and atomization have been taken both at home and abroad to reduce dust concentrations in the air of underground coal mines. In view of the advantages like cost-effectiveness, convenient and strong practicality, atomization has been extensively applied to remove dust in underground coal mines. However, its field practice in underground coal mine is lacking in theoretical guidance. As a consequence, the dust removal efficiency of atomization is not ideal. In particular, the efficiency of respirable dust removal is even below 40% [1–4]. In recent years, scholars begin to investigate atomization characteristics and dust removal efficiency of high pressure atomization. Cheng et al. used an experiment platform specially designed for high pressure atomization to carry out an experiment for analyzing the atomization characteristic of several commonly in the use of nozzles in coal face, and investigated dust removal efficiency on site to determine the relation of water supply pressure to atomization particle size and effect of dust removal [5–8]. Ma et al. took advantage of related theories such as fluid mechanics and aerosol to set up a mathematical calculation model for fractional dust removal efficiency of high pressure atomization in underground coal mines. In addition, they also analyzed the relation of dust removal efficiency with various operating parameters [9–11]. In the use of Fluent, Chen al. investigated impacts of water supply pressure on droplet size, droplet velocity and mist flow field [12,13]. Over the recent years, our research group also carried out a large number of experimental studies on atomization characteristics and dust removal effects of high pressure atomization, and found the relation between dust removal efficiency and various influencing factors [14,15]. Raj Mohan et al. also performed experimental studies regarding characteristics and dust removal efficiency for gas-water atomization, and determined how various operating parameters influence dust removal efficiency [16–18].

Evaluation on dust removal efficiency of high pressure atomization in underground coal mine is usually based on the removal efficiency of total coal dust and respirable dust. The calculation model for dust removal efficiency of atomization established by Chinese scholars can be only used for computing fractional efficiency. In other words, it can only calculate the efficiency of atomization in removing the dust of single particle size. Additionally, the findings of experiments about atomization-based dust removal all focus on

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the qualitative relationship between different influencing factors and dust removal efficiency. Their conclusions cannot be preferably applied to guide on-site engineering design and calculation of atomization-based dust removal efficiency. Therefore, the author set up a theoretical calculation model for removal efficiency of total coal dust and respirable dust based on the calculation model of existing fractional efficiency and the distribution equations of dust size and frequency. On this basis, the relations of different operating parameters and dust characteristic parameters to dust removal efficiency were analyzed. Our findings will provide a theoretical basis for applying high pressure atomization in dust removal to prevent and control dusts on underground coal mining face.

2. Characteristics of high pressure atomization

2.1. Flow coefficient and atomization angle of nozzle

Factors that affect nozzle flow mainly include nozzle configuration, nozzle diameter and water supply pressure. For ordinary single-jet pressure nozzles, their water supply flow can be calculated according to the Eq. (1) [19]:

$$Q = \frac{\pi}{4} C_q d^2 \sqrt{\frac{2p}{\rho}} \times 10^{-3} \tag{1}$$

where Q is the volume flow rate of water supply, m^3/s; and C_q the flow coefficient related to nozzle configuration; d the nozzle diameter, mm; p the water supply pressure, MPa; and ρ the water density, kg/m^3.

At room temperature, flow characteristics and atomization angle of the X-type swirl pressure nozzle commonly used in underground coal mine were measured based on the self-designed experiment platform for high pressure atomization. The diameter of the selected nozzle was 1.5 mm and the corresponding mist flow was in a shape of solid cone. Electromagnetic flowmeter and high speed camera were used to measure water flow rate and atomization angle under 5 water supply pressures (2, 4, 6, 8 or 10 MPa). According to Eq. (1), flow data measured during the experiment were regressively analyzed to acquire the flow coefficient of the nozzle, as shown in Table 1. Besides, atomization photos taken by the high speed camera were imported into Image-Pro Plus 6.0 to calculate atomization angle α. The related calculation results are given in Table 1.

The measurements in Eq. (1) and Table 1 show that the water supply flow of nozzle goes up with the rise of atomization pressure and is in direct proportion to square root of water supply pressure. In addition, the results also indicate that the flow coefficient of nozzle independent of water supply pressure is only associated with nozzle configuration. Regarding a nozzle with fixed structure, there must be a flow coefficient corresponding to it. In the present study, the nozzle's flow coefficient was 0.61. Table 1 also indicates that the atomization angle of nozzle drops slightly with the increase of water supply pressure. For example, when the water supply pressure increases to 10 from 2 MPa, the atomization angle only changes by 2.38°. For the convenience of calculation, the mean value within the interval of water supply pressure (42.18°) is used as the atomization angle of nozzle.

Table 1
Flow rate and spray angle of nozzle under different water supply pressures.

p (MPa)	Q (L/min)	A (°)	C_q	Average α (°)
2	4.01	43.59	0.61	42.18
4	5.67	42.56		
6	7.08	42.01		
8	8.08	41.54		
10	9.12	41.21		

2.2. Atomized particle size of nozzle

With regard to a single-jet atomizing pressure nozzle, atomized particle size can be calculated according to the empirical formula summarized by scholars of the former Soviet Union.

$$\lg \frac{D_{c50}}{\delta} = 4.47 L_p^{-0.133} - 0.35 \lg We \tag{2}$$

where D_{c50} is the mass median aerodynamic diameter (MMAD), i.e., the mass of fog drops with particle size below this value occupies 50% in the total mass of all fog drops, mm; δ the feature size, mm; L_p the Laplace series; and We the Weber number, a parameter describing stability of droplets.

δ in Eq. (2) can be computed by Eq. (3).

$$\delta = d\left(1 - \sqrt{1 - C_q \cos\frac{\alpha}{2}}\right) \Big/ \left(2\cos\frac{\alpha}{2}\right) \tag{3}$$

where d is the nozzle diameter, mm; and α the atomization angle, °. The diameter of the nozzle adopted in this paper is 1.5 mm. Moreover, the flow coefficient of nozzle measured is 0.61 ($C_q = 0.61$) and the atomization angle is 42.18° ($\alpha = 42.18°$). Then, after all related data are substituted into the above equation, Eq. (4) can be obtained as below:

$$\begin{aligned}\delta &= 1.5(1 - \sqrt{1 - 0.61\cos 21.09^0})/(2 \times \cos 21.09^0)\\ &= 0.276\text{mm}\end{aligned} \tag{4}$$

The Laplace series L_p can be calculated based on Eq. (5):

$$L_p = \frac{\rho\sigma\delta}{\mu_L^2} \times 10^{-3} \tag{5}$$

where σ is the liquid surface tension coefficient, N/m; and μ the fluid dynamic viscosity, $N/(m^2 \cdot s)$. Relevant parameters of water in normal state, including $\sigma = 0.072$ N/m, $\mu_L = 1.005 \times 10^{-3}$ Pa·s and $\rho_L = 1000\ kg/m^3$, are selected. Then:

$$L_p = \frac{1000 \times 0.072 \times 0.276}{1.005^2 \times 10^{-6}} \times 10^{-3} = 19675 \tag{6}$$

The computational formula of We is

$$We = \frac{\rho \upsilon^2 \delta}{\sigma} \times 10^{-3} \tag{7}$$

where υ is the axial jet velocity of droplets, m/s, and it can be calculated according to nozzle flow coefficient C_q and water supply pressure p. That is

$$\upsilon = C_q \sqrt{\frac{2p}{\rho}} \times 10^3 \tag{8}$$

Substituting Eqs. (8) into (7) together with related parameters, the value of Weber number is

$$We = 2852.7p \tag{9}$$

Substituting Eqs. (4), (6) and (9) into (2), a equation of atomized particle size. Then, we can obtain:

$$D_{c50} = 10^{2.43 - 0.35\lg p}\ \mu\text{m} \tag{10}$$

Likewise, for an X-type swirl nozzle with a diameter of 1.2 mm, the computation equation of atomized particle size is

$$D_{c50} = 10^{2.39 - 0.35\lg p}\ \mu\text{m} \tag{11}$$

Similarly, in terms of an X-type swirl nozzle with a diameter of 2.0 mm, the equation of atomized particle size is

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