Atomization parameters and fire suppression characteristics of water mist in simulated roadway

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ABSTRACT

Water mist is considered to be one of the most effective ways to suppress fire in coal mines. The structure of an atomization device for water mist was determined based on preliminary research. By regulating the working conditions, including air pressure and water flow volume, we obtained water mist with varying particle size distributions, which proved to be the most important factor for fire suppression. Particle size distribution, characterized by a $V_{99}$ and $V_{50}$, changed from 50 to 1600 $\mu$m during the experiment at a given air pressure (0.6–0.16 MPa) and water flow volume (0.6–1.0 $m^3/h$). The particle size distribution along an axial line can be divided into a wavy flow zone and a fully atomizing zone. Based on the experiments, three types of particle size distributions, 98, 498 and 1013 $\mu$m, were used to test the fire-suppression characteristics of water mist in a simulated roadway with a self-built platform. The result showed that water mist could suppress fire rapidly and the highest temperature dropped from 205 to 10 $^\circ$C within 30 s.

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1. Introduction

Fire is a major disaster during coal-mine production and threatens miners’ safety (NFPA 2006; Ren et al. 2017; Cheng et al. 2017; Ren et al. 2016). On 15 March 2010, 25 miners from Dongxin Coal Mine in Xinmi, Henan, were killed by a cable fire in a roadway. On 6 July 2011, at Zaozhuang Prepared Coal Mine Co., Ltd, a wood and coal fire caused by a blowhole air compressor electrical fault killed 28 people (Liang 2010). Large volumes of toxic gas are produced by combustion, and because of the relatively small space, tunnel fires in coal mines especially endanger miners’ safety. Ventilation disorders that are caused by tunnel fires often result in a serious loss of property (Ray and Singh 2007).
As a new fire-extinguishing technology, water mist is used widely in the fire-protection industry because of its advantages of a high efficiency, a low-cost and personnel and equipment safety (Mawhinney and Richardson 1997, 1996; Mawhinney 1993, 1997; Mawhinney and Back 1998). Water mist for fire suppression and control has gradually become the focus of coal mine-safety researchers (Mawhinney and Dlugogorski 1994; Liu and Kim 2001; Jones and Nolan 1995). Yuan and Lazzara conducted fire-suppression experiments with water mist at the Pittsburgh Laboratory under the National Institute for Occupational Safety and Health (NIOSH) (Yuan and Lazzara 2004). Based on the experimental results, the fire-extinguishing mechanism of water mist is proposed to result from three aspects: fuel-surface cooling, flame cooling and oxygen isolation. Loomis and Mcpherson carried out a series of experiments on water mist in a simulated roadway built by Virginia Tech, and proved that water mist was effective at suppressing fire in fuel-rich combustion mines (Loomis and Mcpherson 1995). Since 2004, Ray and Singh at The Central Mining Research Institute in India have conducted a series of studies in this area, and have indicated that water mist, liquid nitrogen and high-stability nitrogen foam were three major technical means for fire suppression and control in coal mines (Ray and Singh 2005). The experiment that was conducted on a roadway simulation showed that water mist can reduce the downhole combustion intensity, the probability of reversing smoke and the amount of suspended particles in the combustion products and improve the visibility in fire areas (Ren et al. 2016).

Scholars have conducted research on and have explored the application of water-mist technology in the field of coal mine fires (Downie et al. 1995; Heskestad 2002; CMRI 2004; Kong et al. 2018; Ren et al. 2015). Although some achievements have been made, the following problems still exist. First, few studies exist on the mist-field and motion-diffusion characteristics of water mist, especially in ventilation tunnels. The atomization of water mist in the roadway and its movement diffusion affects the fire-extinguishing and cooling effect in fire areas. Therefore, it is necessary to carry out experimental research on the atomization effect and movement diffusion characteristics of water mist in the roadway. Second, compared with the application of water mist in other fields, most experimental studies on the application of this technology in coal mines have been completed based on numerical simulation, however, the results are unsupported by research trials.

Based on the problems above and using a small-scale simulated tunnel test bench and water-mist-generating device in the laboratory, experiments were carried out to study the particle size distribution (PSD) and fire-suppression characteristics of water mist under different ventilation conditions.

2. Mechanism for fire suppression of water mist

Water mist is converted into small particles with a large surface area through an atomizer nozzle. This mist can absorb the heat of the fire area rapidly, and achieve rapid fire extinguishing. Heat exchange between the water mist and the fire area includes heat conduction, heat radiation and heat convection, which are termed sensible heat exchange. Besides these three forms of heat exchange, water mist with its
phase change, can absorb substantial heat to cool the fire area, which is termed latent heat exchange. The total heat exchange during fire suppression consists of a sensible heat exchange and latent heat exchange.

When droplets in the water mist contact the surrounding air, as a result of molecular motion in the droplet, the surrounding air forms a saturated boundary layer with the same temperature as the surface of the droplet. The temperature difference between the saturated air boundary layer and the ambient air results in heat conduction and material exchange.

If we assume a tiny droplet surface of $dS$, sensible heat exchange between the tiny surface and the surrounding air can be expressed as Equation (1):

$$dQ_x = z_{a,w}(T_a - T_b)dS$$  \hspace{1cm} (1)

The latent heat exchange can be expressed as Equations (2), (3) and (4):

$$dQ_q = q_q \cdot dM$$  \hspace{1cm} (2)
The total heat exchange between the droplet and the fire area can be expressed as Equation (5):

\[ dQ_z = dQ_x + dQ_q = \left( \frac{\rho_a \cdot (T_a - T_b)}{C_1} + q_q \cdot \sigma_{a,w}(d_a - d_b) \right) dS \]

Equation (5) suggests that more dispersed particles will have a larger specific surface area, and a faster heat transfer rate will result when the water quantity is constant.

Where \( dS \) is the Droplet surface, \( m^2 \); \( dQ_x \) is Sensible heat exchange, J; \( \rho_{a,w} \) is the Heat-exchange coefficient \( W \cdot m^{-2} \cdot K^{-1} \); \( T_a \) is the Air temperature, K; \( T_b \) is the Boundary layer temperature, K; \( dM \) is the Wet heat exchange volume; \( \sigma_{a,w} \) is the Heat exchange coefficient, \( kg \cdot m^{-2} \cdot s^{-1} \); \( d_a \) is the Moisture content, \( kg/kg_{dry \ air} \), \( d_b \) is the Moisture content of the air layer, \( kg/kg_{dry \ air} \); \( dQ_z \) is the Total heat exchange, J.

3. Experiment platforms

3.1. Testing systems for water-mist PSD

3.1.1. Testing systems and procedures

Figure 1 shows the self-built experimental testing system. Core components included a water-mist atomization device, an air compressor, a plunger pump and a laser particle-size analyzer (Winner318C, China University of Mining and technology). The air source was supplied by an air compressor that provides an air flow rate of 0–360 m³/h with an air pressure of 0–0.8 MPa. Instruments included an electromagnetic flowmeter, a vortex-shedding flowmeter and two pressure gauges (\( P_1, P_2 \)). The laser particle-size analyzer could determine PSDs from 0 to 2000 μm.

Table 1 lists the structural parameters of atomization device. When compressed air flows through the nozzle, the air velocity increases and the static pressure decreases. A maximum was reached at the nozzle throat. At the same time, water was pumped to the device through a water inlet with a high speed. Original water mist was generated during the collision of water and air.

3.1.2. Experimental procedures

The specific experimental procedures were as follows:

| Structure name          | Symbol | Values     |
|-------------------------|--------|------------|
| Air inlet diameter      | \( d_1 \) | 40 mm      |
| Convergence angle       | \( a \)  | 30°        |
| Mist outlet             | \( d_2 \) | 10 mm      |
| Water inlet             | \( d_3 \) | 15 mm      |

\[ dM = \rho_{a,w}(d_a - d_b)dS \]

\[ dQ_q = q_q \cdot dM = q_q \cdot \rho_{a,w}(d_a - d_b)dS \]
1. The experimental system was established according to Figure 1 and every connection was sealed and stable. The laser particle-size analyzer was 1 m away from the water-mist outlet.

2. The air pressure $P_1$ was maintained at 0.06 MPa before the water flow (Q) was changed 0.6–1.0 m$^3$/h in each group with an increment of 0.1 m$^3$/h by adjusting the valve.

3. The air pressure $P_1$ was changed from 0.06 to 0.16 MPa in increments of 0.02 MPa. Step 2 was repeated to measure the water-mist distribution.

Figure 2. Experimental setup, (a) simulated roadway, (b) oil container, (c) arrangement of thermometers.
Figure 3. Relationship between PSD and $Q$ and $P_1$. 
Figure 3. (Continued).
4. The laser particle-size analyzer was stabilized and the atomization device was moved axially with the distance between them (d) being 0–1.5 m. The PSD was determined at each point and at a given work condition for $P_1 = 0.1–0.12$ MPa, $Q = 0.7–0.8$ m$^3$/h.

3.2. Experimental setup to test the fire-suppression characteristics of the water mist

3.2.1. Test system

Figure 2 shows the setup of experiment for fire suppression in roadway. The main instruments were a scale, an oil container, temperature sensors and carbon monoxide transducer (GTH1000, China Coal Science and Industry Group Chongqing Research...
Institute CO. LTD). The self-built roadway was 3 m × 30 cm × 30 cm, and was covered with an insulating layer on three sides. Toughened glass at the front of the setup provided for observation. The room temperature was 15°C.

3.2.2. Experimental procedure
1. The simulated roadway was stabilized and eight temperature sensors were fixed as shown in Figure 2. The diameter of the oil container \( R \) was 6 cm and its height \( h \) was 4 cm. The oil depth \( d_4 \) was 2 cm. The tested heat-release rate was characterized by a mass combustion rate, and was \( 3 \text{ g·m}^{-2} \cdot \text{s}^{-1} \), and its HRR was 1560W when the kerosene was completely burned.
2. The water-mist generating system was regulated under working conditions of \( P_1 = 0.06 \text{ MPa}, Q = 0.6–1.0 \text{ m}^3/\text{h} \) to obtain three PSDs with \( V_{99} = 98 \mu\text{m}, 498 \mu\text{m} \) and \( 1013 \mu\text{m} \) based on the former experiment.
3. The oil was burned and the temperatures was recorded every 5 s. The water-mist system was run at the given working conditions to produce a water mist with a PSD \( V_{99} = 98 \mu\text{m}, 498 \mu\text{m} \) and \( 1013 \mu\text{m} \) near 100 s.

4. Results and discussion
4.1. PSD under different working conditions

Figure 3 shows the change in PSD with \( Q \) for different \( P_1 \). We used \( V_{50} \) and \( V_{99} \) to characterize the PSD, \( V_{50} \) refers to some particles with diameter less than certain particle, and that their whole volume takes 50% of all the particles’. The characteristics of \( V_{99} \) are the same with \( V_{50} \). For a given \( P_1 \), \( V_{50} \) and \( V_{99} \) increased with an increase in \( Q \). During atomization, the jet velocity increased with an increase in pressure. The water membrane broke into a filament or ribbon because of the inertial force.
Intensive vibrations developed from the relative motion of the water membrane lower surface tension and the viscous force itself, which twisted and shortened the liquid membrane and converted the water into droplets.

Water mist with different working parameters is shown in Figure 4.

4.2. PSD along axial line

As shown in Figure 5, the distribution of jetting flow in an open space can be divided into three zones: (1) a jetting core zone, (2) a transition zone and (3) a fully developed zone.

\[
S_n = 0.671 \frac{r}{\beta}
\]  

(6)

Where \( S_n \) - length of jetting core zone, cm; \( r \) - radius of outlet, 0.01 m; \( \beta \) - turbulence coefficient, 0.08 for cylindrical tube.
It can be calculated from Equation (6):

\[ S_n = 8.4 \text{cm} \]

The PSD was obtained for the given working conditions: \( Q = 0.8 \text{m}^3/\text{h}, p_1 = 0.16 \text{MPa} \) (Figure 6). \( V_{50} \) and \( V_{99} \) decreased with an increase in \( d \). When \( d < S_n \), the PSD was larger and decreased rapidly. Then PSD decreased slowly when \( S_n < d < 50 \text{ cm} \). When \( d > 50 \text{ cm} \), water was atomized completely and the particle size remained stable.

The PSD results indicate that water was atomized partly in an atomization device, and the rest of the water continues to atomize in an open space as a function of the air-splitting force (Figure 7). The falling speed of the droplet was maintained at a large value near the centerline. It began to fall away from the centerline and became stable at the edge. This was because the droplets near the centerline had a greater momentum, after leaving the centerline, the interaction between droplet and air increased, and also the air resistance reduced the falling speed of the droplet. When the droplet reached the edge of the water mist field, the droplet was basically balanced by resistance and gravity, and the falling speed of the droplet tended to be stable.

### 4.3. Effect of water-mist particle size on fire suppression

Temperatures \( (T_i, i = 1, 2 \ldots 8) \) along the simulated roadway were measured for different PSDs \( (V_{99} = 98, 498, \text{and} 1013 \mu \text{m}) \). We chose \( T_1 \) and \( T_5 \) to represent the test-point temperatures. \( T_5 \) was located to the top right of the burning oil, and its temperature was the highest, which illustrates the suppression effect clearly. \( T_1 \) represents the surrounding temperature. Other temperatures were changed in the range of \([T_1, T_5]\).

Figure 8 showed the temperature changes of testing points over 140 s. Temperatures increased initially and dropped rapidly after water-mist addition. When first applied, the momentum of the water mist increased the disturbance to the flow field, which would increase the turbulent combustion velocity. Therefore, the flame cannot be effectively suppressed but strengthened, so the temperature rose at first. When the mist continued to move downwards and entered the high-temperature plume, it would be heated and evaporated to generate a large amount of water vapor absorbing a large amount of heat, which can effectively reduce the temperature.

### 5. Conclusions

The PSDs of water mist under different working conditions and the water-mists’ fire-suppression characteristics were investigated and measured. Conclusions are as follows: The water-mist particle size depends mainly on air pressure and water flow volume, which increases with an increase in water flow volume and air pressure. Under given working conditions, the PSD along the axial line consisted of two sectors: a wavy flow zone and a fully atomized zone. Water mist with various PSDs could suppress fire, but the detailed mechanism needs to be studied and validated.
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