Influence of the Droplet Velocity on the Attenuation of Overpressures in a Water Mist

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Abstract. Mist generator is a basic element of systems designed to protect from explosions. It is responsible for forming a suppression barrier between the place of explosion and the zone to be protected. The effectiveness of the system is determined by the capacity of the mist to suppress blast overpressure and impulse. The attenuation capacity, on its turn, depends on mist properties, such as droplet size, water concentration in mist and droplet velocity. The paper examines droplet velocity influence on overpressure and impulse attenuation in mist when the properties of the latter are in the following ranges: droplet size - 15-345 µm; droplet velocity - 5.5-35 m/s; shock wave velocity – 515-718 m/s, droplet impact angle - 90°. The influence of drop velocity on blast attenuation has been assessed according to overpressure and impulse reduction factors.

1. Introduction
Water mist based discharge devices are used in modern explosion suppression systems designed to protect people and equipment in various industrial facilities. Careful selection of water mist characteristics is critical to the design efficiency. Shock wave attenuation and system efficiency are largely determined by drop size and velocity, concentration of water, along with geometric and other properties of the mist [1-3]. The research has shown that shock energy extraction by water mist takes place during the processes of aerodynamic droplet break-up and vaporization of child droplets. Apart from mist characteristics, parameters of gas behind the shock front also have an impact on the aerodynamic break-up of water sprays. Hydrodynamic forces acting on the drops depend on the overpressure of the shock wave, which is functionally related to other parameters of the shock wave, in particular, the velocity and density of air at the wave front. Weber number is often used to study the process of aerodynamic break-up:

\[ \text{We} = \frac{\rho \cdot d \cdot V^2}{\sigma}, \]

where \( \rho \) = density of the gas mixture stream, kg/m³; \( d \) = droplet size, m; \( V \) = relative velocity, m/s; \( \sigma \) = surface tension, N/m.
The critical Weber number at the onset of break-up is $\text{We} = 8 \div 12$; catastrophic breakup completes when $\text{We} > 350$ \cite{1, 4}.

It is essential to properly select mist properties to ensure intensive aerodynamic break-up of the shockwave having expected parameters that are established according to the charge weight, distance and conditions in which the blast take place. They can be calculated according to TM 5-1300 or empirical formulae \cite{5, 6}. Mist and shockwave interaction is, among other factors, influenced by the property of the surface of a water. As is known, surface tension of water is about 0.073 N/m at room temperature. Relative velocity determined in the case where shock wave and water flow are traveling in perpendicular directions, as is often the case during the application of protective systems. Compressed gas density is determined according to shock wave velocity specific heat ratio:

$$\frac{\rho}{\rho_0} = \frac{(\gamma + 1)M^2}{(\gamma - 1)M^2 + 2}$$

Where, $\rho = \text{air density on the shock wave front}$; $\rho_0 = \text{atmospheric density}$, $\gamma = \text{specific heat ratio}$, $M = \text{Mach number}$.

This paper presents the results of an experimental study of overpressure attenuation in a shock tube and in an underground opening. As envisaged by research methodology, water mist with determined drop velocity was generated between the explosion site and pressure sensor.

2. Experimental setup

Series of experiments were conducted to study shock wave attenuation under different droplet velocities. During initial experiments, a shock tube with hydraulic equipment for water mist generation was used for testing. Hydraulic equipment contained a water tank, a high-pressure pump, a hydraulic accumulator, a water distributor and water supply pipes that delivered water under high pressure to nozzles BETE P120 fixed on the shock tube wall. Nozzles were located in the 3 metre-long section of the tube, at 9 cross-sections of the tube with an interval of 40 centimeters (Figure 1). The following are the basic characteristics of the shock tube and hydraulic equipment: diameter of the blast chamber and tubes – 50 cm; blast chamber length – 50 cm; wall thickness – 8 mm, total length of the shock tube – 10.5 m (Figure 2).

![Photo of the shock tube (A) and water supply pipes with nozzles (B)](image)

**Figure 1.** Photo of the shock tube (A) and water supply pipes with nozzles (B)
Figure 2. Scheme of the experiments

Drop velocity in the shock tube was determined according to the results of preliminary experiments. High speed video camera was used to register the time required for a droplet to reach the screen surface located at 50cm from the nozzle. The experiments were conducted in conditions when the pressure in the water discharge system was 4 bar and 8 bar. Under such conditions, water jet velocity was 5.4 m/s and 8 m/s respectively. Given that the volume of the tube segment in which the mist was generated was 0.6 m³, concentration of water in mist was 22.8 L·m⁻³·s⁻¹ when the pressure in the hydro system was 4 bar and 30.0 L·m⁻³·s⁻¹, when the pressure in the hydro system was 8 bar.

Identical blast conditions were provided in each series: charge location – explosion chamber, type of explosive – hexogen, mass of charge - 10 grams, the length of the mist was 3 meters. The water mist had the following properties: the droplet size distribution under both schemes was 15-345 µm, median 180 µm.

Next phase experiments were conducted in an underground opening, where a mist generator with nozzles (BETE P120 model) was installed. The tunnel dimensions were: height – 2.2 m, width – 2.2 m, total length – 150 m, supported by reinforced concrete. The flow rate of generated mist was 4.5-5.3 L·s⁻¹·m⁻³, while drop velocity – 25-35 m/s. The experiments were carried out in the following conditions: charge weight was 2kg (in the first series) and 4 kg (in the second series); the distance from the charge to the mist - 5 m, the length of the mist was 2 meters. For controlling time characteristics, the blast moment and the moment of shock wave arrival were recorded. Overpressures were measured by means of sensors PCB fixed at 8.5 m from the charge. The process of water discharge is shown in Figure 3.

Figure 3. The process of water discharge. A - mist generator, B - The process of water discharge. A - after 12ms from activation of the suppression section (distance from nozzle -1m); C - after 25ms (distance from nozzle -2)
The conditions in which experiments were performed in both phases are given in Table 1.

Table 1. Experimental conditions

| Experimental conditions | Flow rate, L·s⁻¹·m⁻³ | Shock wave velocity, m/s | Overpressure, kPa | Impulse, kPa·ms |
|--------------------------|-----------------------|--------------------------|-------------------|-----------------|
|                          | Without mist          | With mist                |                   | Without mist    |
| Shock tube               | 22.8                  | 515                      | 153               | 76              |
|                          | 30                    | 515                      | 153               | 70              |
| Mist generator in underground opening | 4.5                   | 608                      | 221               | 128             |
|                          | 5.3                   | 718                      | 408               | 236             |

3. Test result

Reduction factors of overpressure $K_p$ and impulse $K_i$ are represented by the following ratio:

$$K_p = \frac{(\Delta P_a - \Delta P_m)}{\Delta P_a} \quad K_i = \frac{(I_a - I_m)}{I_a}$$

where $\Delta P_a$ and $I_a$ is overpressure and impulse without mist, $\Delta P_m$ and $I_m$ is overpressure and impulse with mist.

Table 2 presents overpressure and impulse reduction factor values. Velocity of the gas mixture stream relative to the velocity of the droplet is defined according to the direction of the droplet impact angle – 900.

Table 2. Mist properties and reduction factor

| Drop velocity, m/s | Relative velocity, m/s | Gas density, kg/m³ | We Number | Flow rate, L·s⁻¹·m⁻³ | Reduction factor |
|--------------------|------------------------|--------------------|-----------|-----------------------|------------------|
|                    |                        |                    |           |                       | Overpressure $K_p$ | Impulse $K_i$    |
| 5.4                | 515                    | 2.30               | 1500      | 22.8                  | 0.50             | 0.60             |
| 8                  | 515                    | 2.30               | 1500      | 30                    | 0.54             | 0.61             |
| 25                 | 608.3                  | 2.85               | 2600      | 4.5                   | 0.42             | 0.48             |
| 35                 | 718.8                  | 3.44               | 4380      | 5.3                   | 0.42             | 0.47             |

Table 2 shows that the increase of drop velocity, when other conditions remain unchanged, does not significantly affect the reduction factor. For example, the increase of drop velocity from 25 m/s to 35 m/s, when flow rate is 4.5-5.3 L·s⁻¹·m⁻³, does not affect overpressure and impulse reduction factor. Apparently this is due to the prevailing effect of the water flow on the interaction of the mist and the shock wave.
4. Conclusions
The influence of drop velocity on blast attenuation has been assessed according to overpressure and impulse reduction factors. It was established that under conditions when the We Number ranges from 1500 to 4380, the increase of the drop velocity from 5.5 m/s to 35 m/s does not affect overpressure and impulse reduction factor. Under such conditions, shock wave suppression properties are mainly determined by the water flow rate.

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