Impact of Water Mist Thickness on Shock Wave Attenuation

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Abstract. Explosion protection systems for underground structures are designed to create a suppressing barrier between the site of explosion and the facility to be protected. Studies have shown that water mist, provided that its properties are correctly selected, can effectively reduce shock wave overpressure in tunnels. The influence of droplet sizes and concentration of water in mist on shock wave mitigation processes have been studied by various researchers through experiments and modelling. However, the effect of geometric dimensions of mist on shock wave attenuation in tunnels has not been sufficiently studied.

This paper addresses the influence of water mist thickness on blast overpressure under identical mist properties and explosion conditions in the tunnel. The study of such influence is essential for the proper design of the protective system. Experiments were conducted in the tunnel of the underground experimental base of the Mining Institute, Tbilisi, Georgia. The methodology employed envisaged the measurement of overpressures in the tunnel with the mist generated by the spray system. At different stages of experiments, the water mist thickness was 1.6m, 2.6m and 3.8m. Experiments were carried under the following conditions: charge weight - 2 kg; distance from the charge to the mist - 3.5 m, from the charge to the sensors - 11.5 m, droplet size distribution - 10-260µm, Mist density - 1.45 l/s•m3. In the test zone the height of the tunnel was 2.2 m, width - 2.2 m, cross-section - 4.4m2. The results of the experiments showed that the water mist thickness has an influence on the shock wave overpressure. Under the conditions of experiments carried out by us, the increase of the mist thickness by 3.1 times allowed to reduce the overpressure by 34%.

1. Introduction
Statistical data indicating the fatal outcomes of terrorist and incidental explosions confirm that the existing protective systems fail to meet modern safety requirements and the scope of their application is rather limited. Considering modern challenges, the improvement and perfection of methods applied for the protection of people and infrastructure from the negative consequences of explosion effects remains an urgent task. Designing fast, reliable and high-efficient protection systems requires comprehensive preliminary research.

Current explosion protection methods are basically based on the creation of an explosive energy suppressing barrier between the explosion place and the area that has to be protected. The barrier must ensure reduction of overpressure down to safe value. One of the key issues in designing protective systems is to ensure proper selection of the suppressing barrier characteristics. Analysis has shown that the indicated requirements are met by dispersed liquid, in particular, water mist.
The most essential criterion for the selection of mist properties is the effective reduction of blast overpressures with minimum water discharge. Water mist must create a blast-mitigating barrier with specific geometric and physical parameters soon after the absorber activation. Research showed that shock energy suppression in water mist takes place during the processes of aerodynamic droplet breakup and vaporization of a child droplet. The main characteristics determining the effectiveness of the suppression in water mist are: droplet size, concentration of water phase in mist, velocity of water spraying, mist location and geometric shapes of water mist. Significant knowledge has been accumulated in this area [1,2,3,4]. However, the effect of geometric dimensions of mist on shock wave attenuation in tunnels has not been sufficiently studied.

This paper addresses the influence of water mist thickness on blast overpressure under other identical characteristics of the mist and explosion conditions in tunnel. This relation is important for producing a proper design of the protective system.

2. Experimental Setup
Experiments were conducted in the underground experimental facility of the Mining Institute, Tbilisi. Experimental methodology entailed the measurement of overpressures in a tunnel with mist generated by the system and without mist under same blast conditions. In different cycles of experiments water mist was generated with thickness 1.2 m, 2.6m and 3.2m (figure 1). In the test zone the height of the tunnel was 2.2 m, width - 2.2 m, cross-section area-4.4 m². The used pressure sensors PCB were laid at 0.6m, 1.1m and 1.7m from the floor. The signals were registered on the digital oscilloscopes Tektronix DPO 4034.

![Figure 1. The plan of experiments and the location of the sensors in the tunnel](image)

To generate water mist, a suppression section described in [5] was used. The section consists of the following devices: a water reservoir, a centrifugal pump, a hydro-accumulator, four steel pipes each measuring 4 meters in length and having a diameter of 42mm. The pipes with nozzles are fixed onto the tunnel ceiling and activate upon the receipt of the signal from the control block. In each section pipe are installed 16 nozzles of BETE model TF 8 FCN, in all 64 pieces. The hydraulic circuit of the section is shown on figure 2.
Figure 2. Hydraulic circuit of the suppression section and pipes with nozzles

Upon activation, the section creates an almost equally distributed water mist in the tunnel. When pressure is 10 bar, the droplet size distribution in the water mist formed by these nozzles is 15-345 µm (figure 3).

Figure 3. Water mist in tunnel and droplet size distribution

The density of the mist at all stages of the experiments was the same and amounted 1.23 l/s·m³ (Table 1)

Table 1. Characteristic of mist.

| Nozzle model | Droplet size distribution, µm | Flow rate for 1 nozzle, l/s | Flow rate, l/s | Mist thickness L=1.2 m | Mist thickness L=2.6 m | Mist thickness L=3.6 m | Mist density, l/s·m³ |
|--------------|------------------------------|-----------------------------|----------------|------------------------|------------------------|------------------------|----------------------|
| TF 8 FCN     | 15-345                       | 0.31                        | 6.50           | 14.2                   | 19.8                   | 1.23                   |                      |
3. Test Results
The blast overpressures are recorded without mist and with mist at its various thickness in the following conditions:

- the place of explosion—in the centre of the cross section of the tunnel at a distance of 1.1 m from the floor of working;
- type of explosive—hexogen;
- charge weight—2kg;
  - the distance from the explosion to the cloud – 3.5 m,
  - the distance from the explosion to the sensors –11.5 m.

Overpressure histories without mist and with mist at different thickness are shown in figure 4
Figure 4. Overpressure histories. A - without mist; B - with mist (thickness 1.2m); C - with mist (thickness 2.6 m); D - with mist (thickness 3.8 m).

The results of the experiments are presented in Table 2.

Table 2. Overpressure and impulse without mist and with mist at different thickness

| # | Overpressure, kPa | Pressure impulse, kPa·ms |
|---|---|---|
|   | Without mist | With mist | Without mist | With mist |
|---|---|---|---|---|
| 1-1 | 52 | 51 | 43 | 35 | 182 | 128 | 107 | 87 |
| 1-2 | 53 | 52 | 37 | 30 | 159 | 130 | 93 | 75 |
| 1-3 | 54 | 38 | 33 | 27 | 162 | 122 | 74 | 60 |
| 1-4 | 54 | - | 46 | 26 | 216 | - | 115 | 65 |
| 1-5 | 60 | 45 | 39 | 29 | 180 | 98 | 97 | 72 |
| 1-6 | 53 | 43 | 36 | 26 | 159 | 107 | 90 | 65 |
| 2-1 | 51 | 41 | 41 | 26 | 189 | 102 | 102 | 65 |
| 2-2 | 50 | 41 | 40 | 26 | 172 | 102 | 100 | 65 |
| 2-3 | 49 | 33 | 37 | 26 | 178 | 83 | 92 | 65 |
| 2-4 | 61 | 46 | 44 | 30 | 244 | 115 | 110 | 75 |
| 2-5 | 61 | 41 | 42 | 31 | 213 | 102 | 105 | 77 |
| 2-6 | 50 | 42 | 39 | 26 | 175 | 105 | 97 | 86 |
| Av. | 54 | 43 | 40 | 29 | 186 | 108 | 98 | 71 |

Attenuation effect was estimated by the peak over pressures and positive impulse without mist and with mist: \((P_a-P_m)/P_a\) and \((I_a-I_m)/I_a\), where \(P_a\) and \(I_a\) are overpressure and impulse without mist, \(P_m\) and \(I_m\) - with mist. The mean values of maximum overpressures in water mist of 1.2m, 2.6 m and 3.8 m thickness reduced by 20%, 26% and 46% respectively. A comparatively greater decrease is observed in the impulse - 42%, 47% and 62% accordingly.

4. Conclusions
The results of the experiments showed that the thickness of the water mist influences the overpressure of the shock wave. Under the conditions of our experiments, overpressure was reduced by 34% by increasing mist thickness from 1.2m to 3.8 m.
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