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Theoretical Analysis on the Attenuation Characteristics of Strong Shock Wave of Gas Explosion

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Abstract

In order to study the propagation characteristics of strong shock wave, a theoretical analysis is performed in this paper. Based on some assumptions, the relationships of the peak overpressure and the gas velocity during a gas explosion with the propagation distance were derived by using the explosion and aerodynamics theory. The results show that the peak overpressure of a strong shock wave is inversely proportional to the propagation distance and the cross-section area of the roadway, but directly proportional to the total energy of the gas explosion. However, the gas velocity is inversely proportional to the square root of the propagation distance and the cross-section area, but directly proportional to the square root of the total energy of the gas explosion. According to these results, some preventive measures can be taken to reduce the loss caused by the gas explosions in underground coal mines.

Keywords: gas explosion; strong shock wave; peak overpressure; gas velocity

1. Introduction

Propagating in the roadway of a coal mine, a shock wave of a gas explosion will decay due to the consumption of combustible gas and some irreversible energy loss such as the heat conduction and the thermal radiation within the wave front, and attenuate to a sound wave in the end [1]. Research on the attenuation characteristics of a shock wave is the basis of studying the destructive effects and injury effects of the gas explosion, and it may have great significance to the safety of the underground personnel and the disaster relief of the gas explosions.

Researches on the shock-wave attenuating through various materials were widely performed, such as through polyurethane foam, granular material, filter and so on [2-4]. Experimental investigations on the shock wave attenuating through air were carried out in the rough pipes [5]. A large number of theoretical

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and experimental relations were proposed to describe the dependences of blast-wave intensity with the distance from the center of an explosion [6-7].

These above researches make some explorations on the shock-wave attenuation of the gas explosion, but less on the relationship between the peak overpressure and the propagation distance for the strong shock wave. Based on the explosion and aerodynamics theory, the relationships of the peak overpressure and the gas velocity with the propagation distance were derived to provide theoretical guidance for the disaster relief and the treatment of gas explosions in underground coal mines.

2. Theoretical analysis

After a gas explosion occurs in a roadway, there is mainly a plane shock wave spreading and attenuating along the roadway [8]. To study the propagation law of the shock wave, a plane shock wave model is presented in Fig.1.
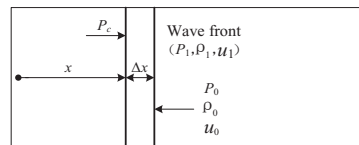

Fig.1. Model of a plane shock wave of a gas explosion

The simplified model only considers the states before and after the wave front as shown in Fig.1. In the explosion process from the beginning to the formation of the shock wave, the state from the prime to the end is assumed to be the ideal state, which has no external friction and heat exchanging because the shock wave is very thin. Other assumptions are shown as follows:

1) Before the gas explosion, the gas state parameters are following: the air pressure is p_0, the density is ρ_0, the temperature is T_0, and the sound velocity is c_0. The space coordinate of the shock wave is defined by the distance of x whose origin is the ignition location. The wave-front parameters are following: the pressure is p_1, the density is ρ_1, the gas velocity is u_1, and the propagation velocity of the wave front is D. These parameters are related to the overpressure of $\triangle p$, and they are expressed by the overpressure [9] as:

$$D = c_0\sqrt{1+\frac{k+1}{2k}\frac{\Delta p}{p_0}}, u_1 = \frac{c_0}{k}(1+\frac{k+1}{2k}\frac{\Delta p}{p_0})^{-1/2}\frac{\Delta p}{p_0}, \rho_1 = \rho_0(1+\frac{k+1}{2k}\frac{\Delta p}{p_0})(1+\frac{k-1}{2k}\frac{\Delta p}{p_0})^{-1} \qquad (1)$$

Here, k is the adiabatic compressibility. The parameters of the wave front can be derived by the equation (1) as:

$$p_1 = p_0 + \frac{2\rho_0 D^2}{k+1}(1-\frac{c_0^2}{D^2}), u_1 = \frac{2D}{k+1}(1-\frac{c_0^2}{D^2}), \rho_1 = \frac{(k+1)\rho_0}{k-(1-2c_0^2/D^2)} \qquad (2)$$

The shock wave is assumed to be a strong one, so $c_0^2/D^2 \rightarrow 0$. The equation (2) can be simplified as:

$$p_1 = p_0 + \frac{2\rho_0 D^2}{k+1}, u_1 = \frac{2D}{k+1}, \rho_1 = \frac{(k+1)\rho_0}{k-1} \qquad (3)$$

2) Because the strong shock wave is very thin, the density within the thin layer is assumed to be a constant and equal to ρ_1. Therefore, the gas mass of M within the layer is equal to that within the range of x in the front of the roadway whose cross-section area is S. That is:

$$M = S \cdot \Delta x \cdot \rho_1 = x \cdot S \cdot \rho_0 \qquad (4)$$

3) The gas velocity in this thin layer is almost a constant because of the strong shock wave, and it is assumed to be the gas velocity of u_1. The pressure inside the layer is defined by p_c and equal to α times of the wave-front pressure, that is $p_c = \alpha p_1$, where α will be determined later. By comparing with these values, the pressure outside the layer can be ignored, that is $p_0 = 0$.

The Newton's second law is established within the thin layer as:

$$\frac{d(Mu_1)}{dt} = S(p_c - p_0) \approx S \cdot p_c = S \cdot \alpha \cdot p_1 \tag{5}$$

By substituting the equations (3) and (4) into the equation (5), we obtain:

$$\frac{d(xS\rho_0 \frac{2D}{k+1})}{dt} = S \cdot \alpha \frac{2\rho_0 D^2}{k+1} \tag{6}$$

As $d/dt = (d/dx) \cdot (dx/dt) = D \cdot (d/dx)$, where $dx/dt = D$, the equation (6) is changed to be:

$$D \frac{d(xS\rho_0 \frac{2D}{k+1})}{dx} = S \cdot \alpha \frac{2\rho_0 D^2}{k+1} \tag{7}$$

$$\frac{dD}{D} = (\alpha - 1)\frac{dx}{x} \tag{8}$$

By integrating it, we can obtain

$$D = Ax^{\alpha-1} \tag{9}$$

Here A is the integration constant. We will determine the constants of A and α by the energy equations. The kinetic energy within the thin layer is:

$$E_K = \frac{1}{2}Mu_1^2 = \frac{1}{2}xS\rho_0(\frac{2D}{k+1})^2 \tag{10}$$

The internal energy of E_T can be included within the range of x in the front of the roadway whose cross-section area is S enclosed by the thin layer [8]. The pressure is p_c, so the internal energy is:

$$E_T = \frac{xS\alpha p_1}{k-1} = \frac{xS\alpha}{k-1}(\frac{2\rho_0 D^2}{k+1}) \tag{11}$$

The total energy of the explosion is E_0, and it is:

$$E_0 = \frac{1}{2}xS\rho_0(\frac{2D}{k+1})^2 + \frac{xS\alpha}{k-1}\frac{2\rho_0 D^2}{k+1} \tag{12}$$

The equation (7) is substituted into the equation (12) as

$$E_0 = 2\rho_0 SA^2 \left\{ \frac{1}{(k+1)^2} + \frac{\alpha}{k^2-1} \right\} \cdot x^{2\alpha-1} \tag{13}$$

Because the total gas content is a constant, the total energy of the explosion is a constant [10]. So E_0 is a constant, and it is independent of x. That is $2\alpha-1 = 0$, $\alpha = 0.5$, and A can be expressed by E_0 as:

$$A = \sqrt{\frac{E_0(k+1)(k^2-1)}{\rho_0 S(3k-1)}} \tag{14}$$

By substituting the equations (14) and (9) into the equation (3), we can obtain the follows:

$$\Delta p = \frac{2(k^2-1)E_0}{(3k-1)S} \cdot \frac{1}{x} \tag{15}$$

$$u_1 = \sqrt{\frac{4(k-1)E_0}{(3k-1)\rho_0 S}} \cdot x^{-0.5} \tag{16}$$

From the equation (15) we can see that the shock wave overpressure $\triangle p \propto 1/x$, $\triangle p \propto E_0$, and $\triangle p \propto 1/S$. From the equation (16) we obtain that: the gas velocity $u_1 \propto 1/x^{0.5}$, $u_1 \propto E_0^{0.5}$, and $u_1 \propto 1/S^{0.5}$.

3. Conclusions

From the results obtained, the following conclusions can be draw:
(1) The peak overpressure of a strong shock wave is inversely proportional to the propagation distance and the cross-section area of the roadway, but directly proportional to the total energy of the gas

explosion. However, the gas velocity is inversely proportional to the square root of the propagation distance and the cross-section area, but directly proportional to the square root of the total energy of the gas explosion. They are $\triangle p \propto 1/x$, $\triangle p \propto 1/S$, $\triangle p \propto E_0$, $u_1 \propto 1/x^{0.5}$, $u_1 \propto 1/S^{0.5}$, and $u_1 \propto E_0^{0.5}$.

(2) According to the relationships of the peak overpressure and the gas velocity with the propagation distance, some preventive measures can be taken to reduce the loss caused by the gas explosions in coal mines, such as by selecting suitable blast resistant construction and antiknock materials, and setting some facilities to prevent gas explosion where is possible and so on.

Acknowledgements

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