Acta Technica *62* (2017), No. 4A, 575–582 © 2017 Institute of Thermomechanics CAS, v.v.i.

Overpressure modification analysis of coal mine blast wave on emergency facilities

LIHUA CAI[2],HUAIMIN LU[3], HAIFENG FANG[2,4],JIHUA FAN[2],QUNBIAO WU[2]

Abstract. In order to discuss the position influence of blast wave on the emergency facilities, the propagation mechanism of the coal mine gas and dust explosion was studied. The theoretical propagation model of the explosion shock wave in the tunnel was established. Based on the comparison of experimental data and theoretical data in explosion, the theoretical expression of the overpressure in gas and coal-dust explosion was modified by introducing the energy correction coefficient. It was found that the value of blast wave overpressure was proportional to the square root of the amount of gas and coal dust, but was inversely proportional to the square root of the transmission distance. And the revised theoretical calculation data was closer to the experimental data in gas and coal-dust explosion.

Key words. Modification analysis, overpressure, gas and coal-dust explosion, emergency facilities,coal mine.

1. Introduction

In China, the security situation of the coal mine is very severe because of the complex terrain, the poor coal bed geological conditions, the big quantity of gassy coal mines and the frequent accidents of gas explosions, water burst, fires and roof collapses [1,2]. According to the research of mine accidents in different countries, more suffering miners were killed by the severe shortness of oxygen, CO poisoning,

---

[1] Acknowledgement-The financial supports from Natural Science Foundation of the Jiangsu Higher Education Institutions of China (Grant No. 14KJD440001), Zhangjiagang Science and Technology Support Program (Grant No. ZKG1314) and Youth Science Fund of Jiangsu University of Science & Technology are greatly appreciated

[2] Workshop 1 - Suzhou Institute of Technology, Jiangsu University of Science & Technology, Zhangjiagang, 215600, Jiangsu, China

[3] Workshop 2 - Shazhou Professional Institute of Technology, Zhangjiagang, 215600, Jiangsu, China

[4] Corresponding author:Fang Haifeng ; e-mail: `fanghale@163.com`

hunger and thirsty after accidents than the direct damage of gas explosions and fires. Therefore, in order to offer a safe and airtight space for suffering miners, many countries have been energetically studying the coal mine refuge chamber [3,4].

The variability of the coal mine disasters determined the uncertainty of the emergency facilities' location. Due to the different natural conditions, production environment and management performance of different coal mines, the occurrence and the development of the accidents was also different. The gas explosion is the most hazardous accident in coal mine. There have been 24 fatal accidents which resulted in more than 100 deaths once since 1949 in China. In these accidents, there were 21 gas accidents which accounted for 88% of the quantity of accidents and 90% of the quantity of deaths respectively. Therefore, this paper selected the gas and coal-dust explosion as the research background, which is the most hazardous accident in coal mines. And the influence of the angles between emergency facilities and roadways and the distances between emergency facilities and the explosion point on the loads the safeguard structures suffered was discussed.

2. Propagation model of shock wave in the roadway

Based on the one-dimensional C-J theory and the ZND model, it is assumed that the explosion spread along the roadway in the form of the plane shock wave after the gas and coal-dust explosion. In order to study the change of the shock wave, the model of the gas and coal-dust explosion is established, as shown in Figure 1. The simplified model only considers the conditions of wave front and wave back. Due to the extreme thin thickness of the shock wave, which was approximately at the nanoscale, the heat exchange and the friction between the shock wave and the wall can be ignored in the propagation process. Other assumptions are as follows:

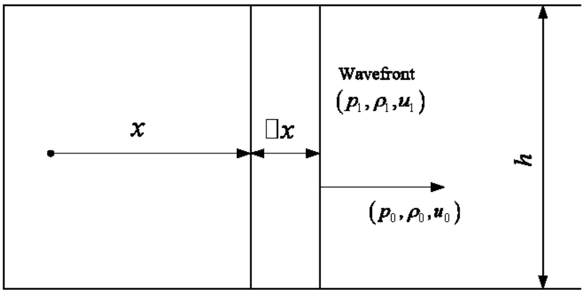

Fig. 1. Model of plane shock wave

(1)State parameters of the air flow in roadway before the gas and coal-dust explosion: the pressure of the wavefront p_{PSWF}, the flow velocity u_{PSWF} , the density ρ_{PSWF}. Each gas parameters of the wavefront can be expressed as followers

[5,6].

$$\left\{\begin{array}{l} p_{PSWF} = p_0 + \frac{2}{k+1}\rho_0 D_p^2\left(1-\frac{c_0^2}{D_p^2}\right) \\ \rho_{PSWF} = \frac{k+1}{k-\left(1-c_0^2 D_p^{-2}\right)}\rho_0 \\ u_{PSWF} = \frac{2}{k+1}D_p\left(1-\frac{c_0^2}{D_p^2}\right) \end{array}\right. \tag{1}$$

Wherein, p0 is the pressure of air; $\rho0$ is the density of air; T0 is the temperature of air; S and h are the cross-sectional area and the height of the roadway, respectively; k is the adiabatic compression coefficient; c0 is the local speed of sound.

(2)Assume the ignition source of the explosion as the origin of the coordinate space. x represents the distance. The air that the gas explosion swept accumulates in the vicinity of the wavefront. The air's quality is concentrated in a very thin layer which thickness is Δx. The shock wave is razor-thin, so Δx is extremely small. The density of the gas within the layer can be assumed as a constant ρ_{PSWF}. The quality M of the gas within the thin layer is equal to the quality of the original air within the roadway in length of x and area of S, as follows.

$$M = Sx\rho_0 \tag{2}$$

(3)Because of the razor-thin shock wave, it can be considered that the airflow's speed which is equal to u_{PSWF} does not change. p_{PN} represents the pressure of the inner layer immediately adjacent to the shock wave. Make $p_{PN} = \beta_1 p_{PSWF}$ and $\beta1$ for an undetermined coefficient. Assumed that the blast is an enormous shock wave, the pressure of the unperturbed gas at the front of the outside of the wavefront can be negligible, compared with p_{PSWF} and p_{PN}. Based on the momentum conservation law, the following formula can be obtained.

$$d\left(M_{u_{PSWF}}\right) = S\left(p_{PN} - p_0\right)dt = S\left(\beta_1 p_{PSWF} - p_0\right)dt \tag{3}$$

The following formula can be obtained by substituting the Eq.2 and the formula $p_0 = \rho_0 c_0^2/k$ into the Eq.3.

$$\left(\beta_1 - 1\right)^{-1}\left(1-\frac{c_0^2}{D_p^2}\right)dD_p\left(1+\frac{1-k}{2k}\frac{c_0^2}{D_p^2}\right)^{-1}D_p^{-1} = \frac{dx}{x} \tag{4}$$

The following formula can be obtained by making Eq.4 of integration.

$$\sqrt{D_p^2+\frac{1-k}{2k}c_0^2}\left[D_p^2\left(D_p^2+\frac{1-k}{2k}c_0^2\right)^{-1}\right]^{\frac{k}{1-k}} = C_p x^{\left(\beta_1-1\right)} \tag{5}$$

Where, Cp is an unknown constant.

The Eq.5 provides the relation between the shock wave's velocity Dp and the distance x. It is difficult to solve the relationship between Dp and x because of the multidimensional relationship in the formula. Reasonable assumptions can make the relationship between Dp and x become clear. From a security standpoint, we can assume that the blast is an enormous shock wave, that is $c_0^2/D_p^2 \to 0$. Eq.5 can be changed to the following formula.

$$D_p = C_p x^{(\beta_1 - 1)} \tag{6}$$

As what mentioned before, the air that the gas explosion swept accumulates in the vicinity of the wavefront. Therefore, assuming the inner pressure of gas asp_{PN}, the internal energy of the gas that is contained in a thin layer in length of x and area of S can be expressed as$E_{PN} = (k-1)^{-1} Sxp_{PN}$. And E_{PK} is the kinetic energy of the gas, which can be expressed as $E_{PK} = Mu_{PSWF}^2/2$. In addition, the total energy E_{P0} the gas of a certain concentration and volume released after explosion is a constant, whose expression is$E_{P0} = E_{PN} + E_{PK} = (k-1)^{-1} Sxp_{PN} + Mu_{PSWF}^2/2$. Substituting the above expression into the Eq.1 and using the Eq.6, we can obtain the following formula $E_{P0} = 2S\rho_0 \left[(k+1)^{-2} + \beta_1/\left(k^2-1\right)\right] C_p^2 x^{2\beta_1 - 1}$. Therefore, if we want to make the total energy E_{P0} be a constant, independent of x, in the condition of certain gas, the variable must be equal to 0. Substituting the above relation into the Eq.6, we can obtain the shock wave's velocity Dp. We can obtain the overpressure of the shock wave by substituting Dp into the formula in the article [7], as follows.

$$\Delta p = \frac{4kp_0}{(k+1)\,c_0}\left[\frac{(k-1)\,(k+1)^2\,E_{P0}}{(3k-1)\,S\rho_0}\right]^{\frac{1}{2}} x^{-\frac{1}{2}} \tag{7}$$

Because the gaseous products the gas and coal-dust explosion generated have much more inflation capability than the solid products, the explosion can be studied as the ideal gas expansion. It is considered that the the energy is released at one time in the initial stage of the explosion .

Modification analysis of propagation model

According to the research in the articles, the explosion energy of one kilogram gas of a concentration of 9.5% is 57.9 MJ at normal temperature and normal pressure. Accordingly, the volumetric energy density of the gas is 3.74 MJ/m3. Substituting k = 1.4, p0 = 101.3kPa, S=7.2m2 and ρ0 = 1.29kg/m3 into the Eq.7, we can get the overpressure of gas explosion, whose unit is kPa.

$$\begin{aligned}\Delta p_1 &= \tfrac{4kp_0}{(k+1)c_0}\left[\tfrac{355300(k-1)(k+1)^2 V}{(3k-1)S\rho_0}\right]^{\frac{1}{2}} x^{-\frac{1}{2}} \\ &= 115.37 V^{\frac{1}{2}} x^{-\frac{1}{2}}\end{aligned} \tag{8}$$

In the article's experimental program , the cross-sectional area S of the roadway is 7.2m2 and the experiments are the pure gas explosion experiments. And the volumes of the gas-air mixture of a concentration of 9.5% are 100m3 and 200m3 in the experiment. So we can obtain the theoretical calculations by taking the value of x into the above, with the gas-air mixture's accumulation volume of 100m3 and 200m3. The comparisons of overpressure in experimental and theoretical data in gas explosion are shown in Table1 and Figure 2.

According to the research in the article, the explosion energy of one kilogram coal-dust is 6.62MJ. Substituting k = 1.4, p0 = 101.3kPa, S=7.2m2 and $\rho0$ = 1.29kg/m3 into the Eq.7, we can obtain the overpressure of gas and coal-dust explosion, whose unit is kPa.

$$\begin{aligned}\Delta p &= \frac{4kp_0}{(k+1)c_0}\left[\frac{(355300V+6620200m)(k-1)(k+1)^2}{(3k-1)S\rho_0}\right]^{\frac{1}{2}} x^{-\frac{1}{2}} \\ &= \left(115.37V^{\frac{1}{2}}+498.02m^{\frac{1}{2}}\right)x^{-\frac{1}{2}}\end{aligned} \tag{9}$$

Experiment schemes of the article [9] are shown in Table 2. The corresponding theoretical values are calculated and compared with the experimental values, as shown in Table 3 and Figure 3.

Table 1. Theoretical data and experimental data of overpressure in gas explosion

Volume /m^3	Experiment								
		Distance / m							
		10	30	40	60	80	100	120	140
100	Experiment 1	120	171	180	136	167	151	139	128
	Experiment 2	160	167	168	163	145	137	131	129
	Experiment 3	156	159	161	163	130	125	138	130
	Calculation 1	363	211	182	149	128	115	105	97
200	Experiment 4	432	295	288	286	269	261	258	250
	Experiment 5	450	324	311	302	284	270	261	256
	Experiment 6	350	308	285	265	264	255	248	243
	Calculation2	515	297	258	210	182	163	150	137

Table 2. Experiment condition of gas and coal-dust explosion

Experiment	Volume of gas mixture / m^3	Density of gas / %	Quantity of coal-dust / kg	Laying range of coal-dust/m
1	200	9.5	100	35-100
2	200	9.5	100	35-100
3	200	9.5	110	35-85

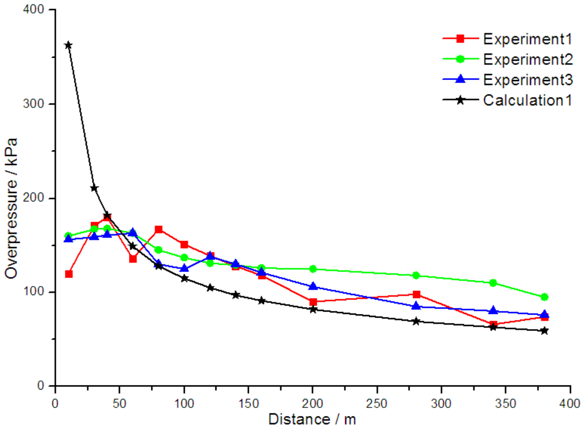

Fig. 2. Comparison of overpressure in experimental data and theoretical data in gas explosion

Table 3. Theoretical data and experimental data of overpressure in gas and coal-dust explosion

		20	30	40	60	80	100	120
100kg coal-dust, 200m^{3}gas mixture	Experiment 1	165	137	357	486	1310	716	653
	Experiment 2	128	208	292	510	1070	820	532
	Calculation 1	1370	1119	969	792	684	613	559
110kg coal-dust, 200m^{3}gas mixture	Experiment 3	115	130	381	559	1210	681	431
	Calculation 2	1531	1250	1083	884	765	685	626

From the figures and tables listed above, we can find that the values of the actual experiments' explosion overpressure decay regularly after increasing to the maximum with the distance to het detonation point. For the gas and coal-dust explosion, because raising lots of coal-dust need to consume a portion of shock wave's energy, the values of the overpressure in the front of the coal-dust laying range are lower than those of the pure gas explosion. Then the coal-dust cloud raised by the shock wave contributes to the explosion, causing the explosion overpressure rising rapidly.

Based on the above analysis, in order to make the calculation values more relevant to the experimental values, the theoretical expression of the overpressure in gas and coal-dust explosion is fixed by introducing the energy correction coefficients, ζ_1 and

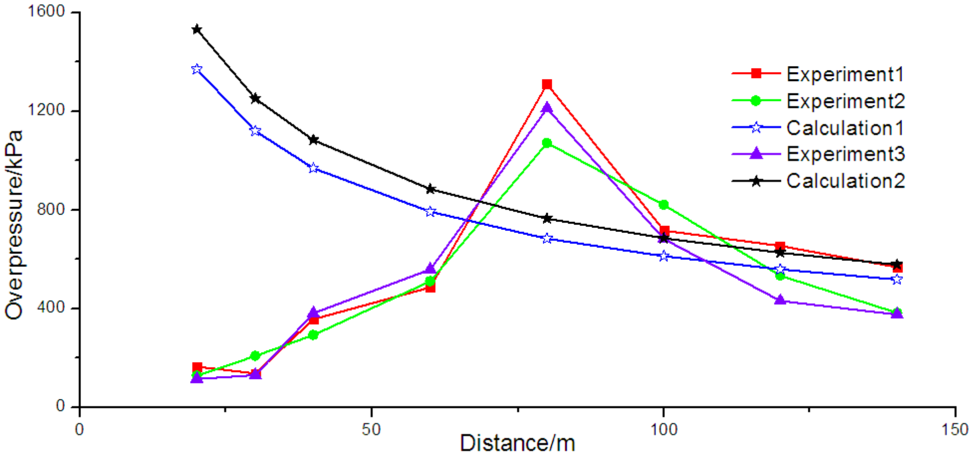

Fig. 3. Comparison of overpressure in experimental data and theoretical data in gas and coal-dust explosion

ζ_2, as shown in the Eq.10.

$$\Delta p = \left(115.37\zeta_1 V^{\frac{1}{2}} + 498.02\zeta_2 m^{\frac{1}{2}}\right) x^{-\frac{1}{2}} \tag{10}$$

In order to determine the above two correction coefficients' expressions, the experimental data and theoretical data in gas explosion is compared and analyzed firstly.

3. Summary

The propagation mechanism of the gas and coal-dust explosion is studied. The theoretical propagation model of the explosion shock wave in the roadway is established. The experimental data and the theoretical data in explosion are compared. And the following conclusions are obtained.

(1)It is found that the value of blast wave overpressure is proportional to the square root of the amount of gas and coal dust, but is inversely proportional to the square root of transmission distance. Therefore, in order to prevent the destruction of blast wave, the emergency facilities close to the explosion-prone point should have higher explosion impact resistance.

(2)The theoretical expression of the overpressure in gas and coal-dust explosion is fixed by introducing the energy correction coefficients, $\zeta 1$ and $\zeta 2$. It can be found that the revised theoretical calculation data are closer to the experimental data in gas and coal-dust explosion, which shows that the energy correction coefficients introduced in this paper can make up for the lack of the original theoretical formula.

(3)The emergency facilities should be able to meet the requirements of the variational mining locations and have the mobile convenience. The emergency facilities should extend to the middle of the serious injury zone, which can make the most of the role of the safety risk facilities.

References

[1] Dejan. V. Petrovic,Milos. Tanasijevic, Vitomir. Milic,: *Risk assessment model of mining equipment failure based on fuzzy logic.*Expert Systems With Applications*41* (2014), No. 18, 8157–8164.

[2] Cheng. J, Wei. L.: *Failure Modes and Manifestations in a Mine Gas Explosion Disaster.*Journal of Failure Analysis and Prevention *14* (2014), No. 5, 601–609.

[3] R. H. Gutierrez, P. A. A. Laura: *Fundamental frequency of vibrating rectangular, non-homogeneous plates.* Applied Acoustics *18* (1985), No. 3, 171–180.

[4] Sha. S. Chen. Z, Jiang. X: *Influences of obstacle geometries on shock wave attenuation.*Shock Waves*24* (2014), No. 6, 573–582.

[5] Zeitoun. D. E: *Microsize and initial pressure effects on shock wave propagation in a tube.* Shock Waves *24* (2014), No. 5,515–520.

[6] Ye. Q, Jia. Z. Z: *Study on comprehensive gas control techniques and practice in coal mines.*Combustion, Explosion, and Shock Waves*50* (2014), No. 4, 424–428.

[7] Liu. X. W: *Turbulence induced additional deceleration in relativistic shock wave propagation: implications for gamma-ray burst.* Astrophysics and Space Science *342* (2012), No. 1, 113–116.

Received November 16, 2016