EFFECT OF IGNITION ENERGY ON COAL DUST EXPLOSION

by

Tao BAN[a,b], Zhong-Qiang LIU[b,*], Guo-Xun JING[a], Lei CHENG[a],
Yu-Lou WU[a], and Le PENG[a]

[a] College of Safety Science and Engineering, Henan Polytechnic University, Jiaozuo, China
[b] School of Mathematics and Information Science,
Henan Polytechnic University, Jiaozuo, China

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Coal dust explosion is of great importance for both theoretical analysis and practical applications. However, there is not a complete theory to reveal its mechanism. Here we show that the ignition energy plays an important role. An experiment is designed using different volatile coal dusts under different ignition energies, and the results are extremely helpful for avoiding coal dust explosion and can be also used for verification of a new theory.

Key words: *coal dust explosion, ignition energy, lower explosion limit, fractal calculus, release oscillation*

Introduction

Dust explosion refers to the phenomenon that a violent chemical reaction occurs when combustible dust with a specific concentration is dispersed into air or a combustion-supporting environment to form a dust cloud and after being ignited by proper energy within a limited space. In the process of dust explosion, the rapid propagation of flame in the medium leads to a rapid rise in temperature and a sharp increase in pressure in the system. In the limited airtight or semi-airtight space, the energy release rate is much higher than that of the general combustion process, so the risk of dust explosion is extremely huge [1-4].

At present, the research work about dust explosion mainly focuses on the influencing factors such as ash concentration, particle size, pressure, temperature, and oxygen concentration, but only few scholars paid attention to ignition energy [5-7]. Current studies and practices show that the power required to ignite combustible dust is much higher than that needed to ignite combustible gas, and ignition energy has a significant impact on dust explosion [8, 9]. However, due to the lack of systematic research, the understanding of its mechanism is preliminary, further experimental and theoretical analyses are strongly needed.

A coal dust explosion is a fast and complicated two-phase dynamic process. The combustion process of coal dust consists of two key links: particles are heated to release volatile matter, which is then mixed with air to form a combustible gas. In the process of heat conduction during coal heating/cooling, the heat conduction equation can be written in the form [10]:

$$\frac{\partial T}{\partial t}=\frac{\lambda}{\rho C_p}\left(\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}\right), \quad (0<r<R) \tag{1}$$

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[*] Corresponding author, e-mail: lzq454000@163.com; 13939195683@163.com

where ρ [kgm^{-3}] is the filling density of coal sample, C_p [Jkg^{-1}K^{-1}] – the specific heat capacity, λ [Wm^{-1}K^{-1}] – the thermal conductivity, T [K] – the temperature of coal body, r [m] – the distance from a certain point in coal to the axis, and R [m] – the radius of coal pillar.

Its initial condition is:

$$T\big|_{t=0} = T_0$$

and its boundary condition is:

$$\frac{\partial T}{\partial r} + \frac{\alpha}{\lambda}(T - T_0) = 0 \quad (r = R, \quad t > 0), \quad T = T_\alpha \quad (r > R, \quad t \geq 0)$$

Among them, T_0 [K] is the initial coal temperature, T_α [K] – the environmental temperature, α – the apparent heat transfer coefficient, $\alpha = \lambda/\rho C_p$. The metamorphism degree, moisture concentration, M_{ad}, ash concentration, A_{ad}, volatile concentration, V_{ad}, and voidage of the same coal sample are the same though the specific heat capacity of coal is affected by the degree of coal metamorphism, moisture, ash content, void fraction and temperature. Only the temperature has an effect on the specific heat capacity of the coal sample. At the same temperature, the specific heat capacity C_p of loose coal samples is in line with the concentration of dry ashless volatile matter, V_{daf}, which can be expressed [11]:

$$\begin{cases} C_p = 1.86 V_{daf} + 802.4 \quad (30\,^\circ\text{C}) \\ C_p = 3.62 V_{daf} + 1100.0 \quad (60\,^\circ\text{C}) \end{cases} \tag{2}$$

where $V_{daf} = V_{ad} \times 100/(100 - M_{ad} - A_{ad})$.

Scott *et al.* proposed a formula for calculating the calorific value of anthracite in [12]:

$$Q_{gr,ad} = 34389 + 176.1 V_{ad} - 388.9 A_{ad} \tag{3}$$

In the early 1980's, a formula for calculating the heating quantity of bomb cylinder of coal was proposed by Beijing Mining Bureau [12]:

$$Q_{b,ad} = (aFC_{daf} + bV_{daf})\left[\frac{100 - (M_{ad} + cA_{ad})}{100}\right] \tag{4}$$

From the previous four formulas, the calorific value and heat transfer speed of coal are closely related to the coal quality index. The calorific value of coal increases with the increase of volatile matter and fixed carbon content, and decreases with the increase of ash and water content. The calorific value of coal directly affects the explosive strength of coal. In general, a volatile release is not only related to its own volatility, but also closely related to the size of ignition energy. Therefore, exploring the influence of ignition energy also helps to understand the mechanism of coal dust explosion. As the most important characteristic of explosion sensitivity, accurate measurement of the lower explosion limit ρ_{LEL} (the lowest mass concentration of coal dust cloud that can be sustained by an explosion – LEL) is particularly critical. Kuai *et al.* [13] found that the test results of the lower explosion limit were related to ignition energy. However, there is no uniform regulation on the selection of ignition energy in the current detection standards of the lower explosion limit, thus the test method needs to be improved. In order to study the influence of ignition energy on explosion brisance, maximum pressure rising rate $(\mathrm{d}p/\mathrm{d}t)_{\max}$, maximum explosion pressure $P_{\max}$ and combustion duration t_{c}, and sensitivity characteristics, a 20 L spherical explosion test system is adapted to conduct explosion test for high, medium and low volatile coal dusts in this paper.

Experimental system

Experimental sample

In this section, three types of coal (sample 1, sample 2, sample 3) are selected for the test after being crushed and screened (standard 200 sieve mesh). The industrial analysis of three types of coals is shown in the tab. 1.

Table. 1. Industrial analysis of three different coal dusts

Sample No.	M_{ad} [%]	A_{ad} [%]	V_{ad} [%]	FC_{ad} [%]	A_d [%]	V_d [%]	V_{daf} [%]	FC_d [%]
Sample 1	2.68	3.94	40.98	52.4	4.05	42.11	43.89	53.84
Sample 2	1.71	16.42	28.38	53.49	16.70	28.87	34.66	54.43
Sample 3	1.08	8.07	19.40	71.45	8.16	19.61	21.35	72.23

Experimental equipment and methods

The 20 L spherical explosion test system consists of the device body, control system, and data acquisition system. The structure is shown in fig. 1. The device body is mainly composed of a double-layer stainless steel ball with a water-cooling jacket, a dust tank, and a gas distribution system, which is a crucial part of the test system. First, the volume of the dust tank was 0.6 L, and the dust tank was pre-aerated to 2 MPa before experiment. Then, coal dust was injected into the ball by the dispensing nozzle in the high pressure air to form a highly turbulent coal dust cloud. The chemical ignition heads of igniter in the explosion experiment were, respectively, 1, 2, 5, 8, and 10 kJ. The chemical ignition device used in the test was made of zirconium powder, barium nitrate, and barium peroxide with a mass ratio of 4:3:3.

Results and analysis

Analysis of typical coal dust explosion process in a 20 L explosion ball

Up to now, the mechanism of coal dust explosion is not very clear because of its complicated physical and chemical process. For the particle ignition, the mechanism of a coal dust explosion mainly includes gas-phase ignition mechanism and surface heterogeneous

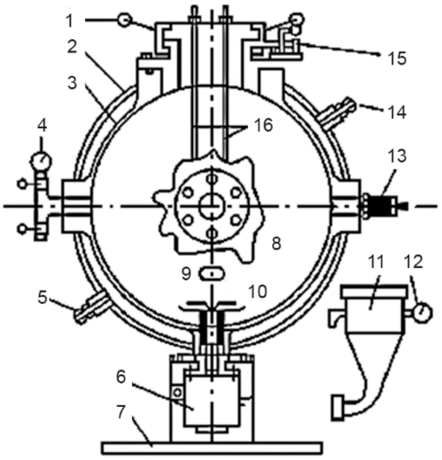

Figure 1. The 20 L spherical vessels for explosion test; *1 – sealed cap, 2 – outer jacket, 3 – inner jacket, 4 – vacuum meter, 5 – circulation water inlet, 6 – mechanical two-way valve, 7 – pedestal, 8 – sightglass, 9 – vacuum orifice, 10 – scattered valve, 11 – dust container, 12 – electro connecting pressure gauge, 13 – pressure sensor, 14 – circulation water outlet, 15 – safety and limit switches, 16 – ignition rod*

ignition mechanism. By comparison with combustion, the explosion process of coal dust generally contains two typical reaction processes: the precipitation and homogeneous combustion of volatile gases and heterogeneous combustion of solid carbon (usually incomplete combustion), which plays a crucial role in the overall reaction rate of coal dust [14]. There is no uniform criterion for the ignition mechanism of specific powder and air mixtures. It is generally believed that a gas-phase reaction dominates the powder air mixture for large particle dust which has slow heating rate. In contrast, a non-uniform surface reaction dominates the mixture for small particle dust which has its rapid heating rate. With certain conditions, gas-phase ignition and surface heterogeneous ignition can coexist and transform each other.

The pressure-time curve of a typical coal dust explosion obtained in the experiment is shown in fig. 2. The P_{max} is a typical thermodynamic characteristic, representing the total energy released by the explosion; $(\mathrm{d}p/\mathrm{d}t)_{\mathrm{max}}$ is the maximum slope of the pressure-raising section of the sampling curve, t_{c}, is the duration from ignition to maximum pressure, all of them are dynamic characteristic parameters that characterize the speed of energy release, namely the combustion rate [15]. For the coal dust explosion in the ball, the explosive energy of chemical igniter improves the surface temperature of coal dust particles, then the volatile combustible gas released from coal particles quickly catches fire in the gas phase. The energy released by the above process also accelerates the pyrolysis of the dust particles around the burning particles, making combustible volatile gases escaping from a large number of particles, which are involved in combustion accompanied with the heterogeneous combustion of pyrolyzed coal particles (generally incomplete process). That is the combined release of energy, which causes the gas in the sphere to expand and creates an explosion overpressure.

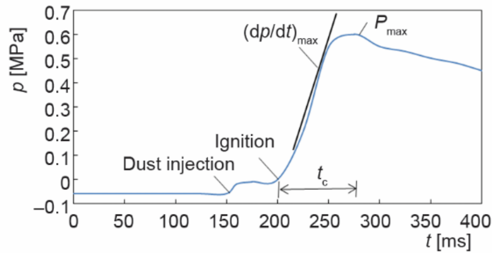

Figure 2. Typical coal dust explosion pressure rise curve in 20 L explosion ball

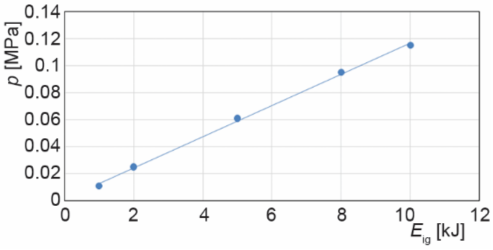

Figure 3. Evolution of p_{ig} with ignition energy

The deflagration behavior of the ignition device itself

Unlike electric spark ignition, chemical ignition will spray hot combustion products and induce a certain degree of turbulence. The heat released by the igniter increases the pressure inside the vessel, which is called ignition boost, p_{ig}. By setting a blank experiment (that is, no coal dust is added), it is found that p_{ig} is linearly related to ignition energy, as shown in fig. 3.

Influence of ignition energy on explosion characteristics

Thermodynamic property

Three samples of coal dusts with different volatile components were selected and ignited with the energy of 1, 2, 5, 8, and 10 kJ at a mass concentration of 400 g/m^3, respectively. The results are shown in fig. 4. The P_{max} increases with the increase of ignition energy, indicating that the increase of ignition energy can significantly increase the total energy released by the dust explosion system. To deduct the energy released by the igniter, we introduce a specific pressure, p_r:

$$p_r = \frac{p_{\max} + p_0 - p_{\text{ig}}}{p_0}$$

where p_0 is the initial pressure, $p_0 = 0.1$ MPa, p_r of sample 1 with higher volatility almost did not change with the ignition energy, indicating that the ignition energy had no significant influence on the energy released by the explosion of highly volatile coal dust. The p_r of medium volatile coal dusts increases slowly with the increase of ignition energy. However, the low volatile coal powder cannot be ignited by 1 kJ energy. In the process of ignition, the energy increase from 2 kJ to 10 kJ, and the net energy released by the explosion rises significantly. The gas-phase ignition mechanism of dust holds that the explosion energy depends on the combustible volatiles released by the particles, while the ignition energy [16], which seriously controls the volatility of coal powder, leads to the increase of its explosion energy with ignition energy. Due to the high volatility of sample 1, the efficient deflagration process is more similar to gas combustion, and the combustion behavior has little relation with ignition energy. The above results indicate that volatile components play a key role in a coal dust explosion. Under the excitation of low ignition energy, medium and low volatile coal dust can not be fully burned or even ignited, which is called the adverse effect of the explosion.

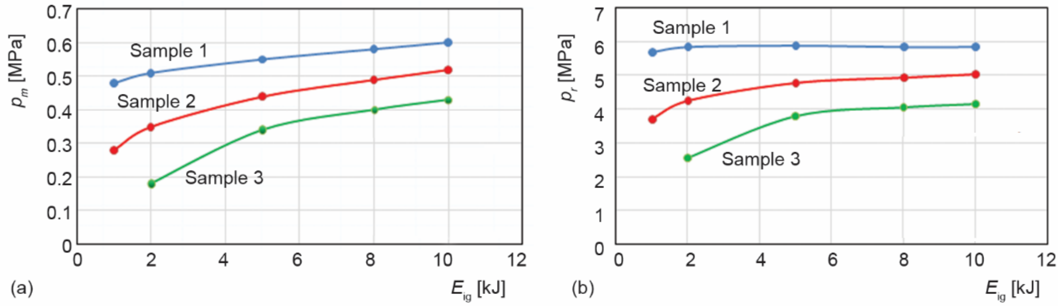

Figure 4. Evolutions of p_m and p_r with ignition energy, for three kinds of coal dust

Medium volatile coal dust was selected to lucubrate the adverse effects of the explosion. The concentration of coal dust used was $\rho_{\text{LEL}} \sim 700$ g/m^3, and the results are shown in fig. 5. When dust concentration is low, the influence of ignition energy on p_r gradually decreases. When the mass level of coal dust reaches above 600 g/m^3, all curves tend to coincide, and it basically eliminates the adverse effect of explosion. The mass concentration of coal powder should be reduced as far as possible in the process of production, storage, transportation, and use, and heat source should be eliminated or ignition intensity should be reduced. It is feasible to control the explosion risk by controlling the intensity of heat or fire source when the existence of low mass coal dust cloud is unavoidable. Low mass concentration dust cloud has low flame propagation efficiency due to the large particle gap [17], then the particle volatility efficiency becomes a limiting factor. Therefore, explosion energy is sensitive to ignition energy. Bigger dust mass concentration can improve the thermal transfer efficiency, shorten the explosion induction time and make flame proliferation more adiabatic and efficient

[13], resulting in a significant increase in volatile efficiency. Coal dust explosion behavior is controlled by a gas-phase combustion process and no longer restricted by ignition energy. Therefore, the adverse explosion effect of the coal dust cloud with high-quality concentration is not significant. In addition, it can also be known from fig. 5 that the lower explosive limit of medium-volatile coal powder decreases sharply with the increase of ignition energy.

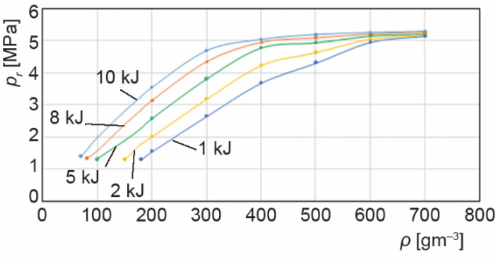

Figure 5. Evolutions of p_r with medium volatile coal in various ignition energies

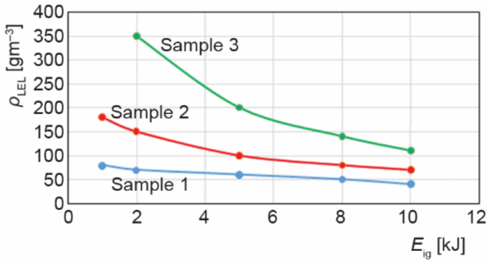

Figure 6. Evolutions of the lower explosion limit with ignition energy for three coal dust

Lower explosion limit

Three kinds of pulverized coals were ignited by energy of 1, 2, 5, 8, and 10 kJ, respectively, and the lower explosive limit of pulverized coal under different ignition energies was measured, as shown in fig. 6. In this paper, $p_r \geq 1.3$ recommended by EN 14034-3 was selected as the criterion of the explosion. Because the high ignition energy leads the pulverized coal of low mass concentration to precipitate enough volatile matter to sustain the spontaneous outburst, the lower explosion limit of low volatile coal powder decreases sharply with the increase of ignition energy. The lower explosion limit of high volatile coal dust is less affected by ignition energy precisely because of its high volatility, and the explosion process is similar to gas combustion. Cashdollar and Chatrathi [18] believed that the actual explosion limit should be independent of ignition energy, so it can be seen that it is suitable to use 2 ~ 10 kJ power to test the lower explosion limit of highly volatile coal powder. For the low volatile coal powder, although the range of ignition energy, which keeps the lower explosion limit stable, is not obtained, it is not recommended to test with the energy higher than 10 kJ. The over-strong ignition energy will cover the explosion process of the dust itself, and even create an illusion that the low mass concentration dust clouds, which cannot cause the flame to multiply itself, can be ignited [19]. Considering that the lower explosion limit of low volatile coal powder tends to be stable in the range of 8 ~ 10 kJ, it is recommended to use 8 ~ 10 kJ ignition energy to test the lower explosion limit of low volatile coal powder.

Discussion and conclusions

To improve the test method of coal dust explosion, the explosion behavior of high, medium and low volatile coal dust under different ignition energies is experimentally studied in a 20 L spherical explosion test system. The experimental results are extremely important to make a criterion for practical applications, and they can also be used to verify a new theory for the explosion. The two-scale thermodynamics [20, 21] might be a potential candidate to model the coal dust explosion process using two scales, one is the big scale where eq. (1) works, the other is the smaller scale where fractal calculus [22-25] has to be used to describe the effect of dust concentration on explosion mechanism. The pressure oscillation given in fig. 2 can be modelled by a non-linear oscillation model. Liu *et al.* [26] suggested a fractional non-linear system for release oscillation, and Lin *et al.* [27-32] revealed the low frequency of release oscillation, which can be extended to study the release of volatile matter from dusts. Its frequency-amplitude relationship is of great importance to determine the maximal released energy, explosion ratio and duration.

A coal dust explosion is a fast and complicated two-phase dynamic process. The combustion process of coal dust consists of two key links: particles are heated to release volatile matter, which is then mixed with air to form a combustible gas.

We give the following conclusions:

- Increasing ignition energy can improve the combustion rate of coal dust and make coal dust deflagration more violent. By comparation with the high volatile coal dust, low volatile coal dust explosion is more significantly affected by ignition energy.
- Low volatile coal dust at low mass concentration has an adverse explosion effect that can not be fully ignited by low ignition energy. With the increase of coal dust mass concentration, the adverse explosion effect is continuously weakened until disappearing. The adverse impact of the explosion has positive guiding significance for accident prevention. In other words, it is feasible to control the explosion risk by eliminating heat source or reducing the intensity of ignition when the existence of low mass coal dust cloud is unavoidable, or the dust removal is difficult and costly in coal production.
- Ignition energy is a crucial factor affecting the measurement accuracy of the lower explosion limit of coal dust. The lower explosion limit of low volatile coal dust decreases sharply with the increase of ignition energy. When testing the lower explosion limit of low volatile coal dust, 8 ~ 10 kJ ignition energy should be selected.

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