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Full Length Article

Minimum explosion concentration of coal dusts in air with small amount of $CH_4/H_2/CO$ under 10-kJ ignition energy conditions

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ABSTRACT

A 20-L spherical explosion chamber was used to investigate the minimum explosion concentration (*MEC*) of coal dusts with small amount of flammable gas which is lower than its lower explosion limit (*LEL*). Two dust samples (anthracite coal and bituminous coal) and three flammable gases (CH_4, H_2 and CO) were tested. Two methods respectively based on overpressure and combustion duration time were used to determine the *MEC* of the hybrid mixtures. Experimental results show that the explosion of hybrid mixtures occurs when both dust and gas concentrations are lower than the *LEL* or *MEC* of the single substances. As flammable gas concentration increases, either explosion pressure (P_{ex}) and explosion pressure rise $(dp/dt)_{ex}$ increase or the *MEC* decreases for all the hybrid gas-dust mixtures as a general trend, showing a strong concentration effect. At the same concentration of coal dusts, the addition of CH_4 poses a higher explosion risk than the other two flammable gases. Moreover, it was found that the results of *MEC* determined by both methods agree each other well, suggesting that both methods are valid to determine *MEC* of hybrid mixture in the synergic explosion region. The distribution of experimental data in the explosion regimes shows that the restricted areas defined by empirical formulas are insufficient from safety considerations.

1. Introduction

The hybrid mixtures of combustible dusts and flammable gases are widely existing in coal mining, petrochemical, metallurgical, textile and pharmaceutical industries [1–3]. The hybrid mixture explosions of coal dust, methane and hydrogen can occur in the processes of coal mining, transportation, storage and utilization, with great losses of life and property. For instance, methane (CH_4) can be released during the mining process [4–7], and flammable gases including CH_4, carbon monoxide (CO) and hydrogen (H_2) can be generated from the self-heating, spontaneous combustion, or pyrolysis processes of coal [8–10]. It may pose a higher explosion risk in the industrial processes of dust handling with presence of these flammable gases.

Similarly with investigations on gas explosion characteristics [11,12], most attention has been paid to the explosion severity of hybrid mixtures including explosion pressure (P_{ex}), explosion pressure rise $(dp/dt)_{ex}$ and explosion index (K). Agrida et al. [13] investigated the explosion behaviour of hybrid mixtures of nicotinic acid dust and methane and pointed out that these explosion behaviours can be drawn on a same graph with 5 different regimes, i.e., dust driven explosion, dual-fuel explosion, gas driven explosion, synergic explosion and no explosion. Li et al. [14] used a standard 20-L explosion spherical vessel to investigate the explosion characteristics of hybrid mixtures, the results showed that both P_{ex} and $(dp/dt)_{ex}$ present an increasing and then decreasing trend with increasing CH_4 contents in the hybrid mixtures, and the peak values appears at the point that mole fraction of CH_4 is 10%. Kosinski et al. [15] studied the explosion characteristic of carbon black with a low content of volatiles and propane and found that it is possible to obtain flame propagation even when the concentration of gaseous fuel is below the lower flammability limit. Hassan et al. [16] proposed a predictive model based on experimental data from literature to assess the probability of a dust explosion occurrence in a given environment. Sanchirico et al. [17] and Addai et al. [18] conducted experiments in a 20-L spherical vessel to prove the validity or limitations of some formulas for various combinations of dust and gases. Ji et al. [19] investigated the vented hybrid mixture explosions of lycopodium dust and methane and found that the addition of methane to lycopodium dust led to an increase in both maximum explosion pressure and the

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maximum rate of pressure rise and a decrease in the optimum dust concentration. Kundu et al. [20] studied the explosion characteristics of methane-coal dust hybrid mixtures and observed that the violence of coal dust explosions increases significantly in the presence of methane.

Minimum explosible concentration (*MEC*), as a crucial sensitivity parameter in dust explosion evaluation and prevention, is the concentration boundary above which a dust-oxidant mixture will propagate a flame in the presence of adequate ignition source. *MEC* has been found to be influenced by particle size, ignition energy, fuel properties and gas conditions, as well as explosion criterion [21–23]. Yuan et al. [22] argued that the standardized method with a fixed ignition delay (t_{ig}) of 60 ms based on explosion pressure (P_{ex}) may overestimate the *MEC* because P_{ex} strongly depends on t_{ig} (i.e., P_{max} may not occur at t_{ig} of 60 ms), and proposed an alternative method by using combustion duration time (t_{com}) to determine the *MEC* based on the test results of overpressure evolution in 20-L spherical chamber. Their results [22] showed that the values of *MEC* determined by using t_{com} were slightly lower than the data obtained by the standardized method. Addai et al. [23] further studied the explosion characteristics of three component hybrid mixtures and the results demonstrated that a hybrid explosion is possible even when dust, gas and vapor concentrations are respectively lower than their *MEC* of dust and *LEL* of gas and vapor.

Most of the above studies only focused on dust/gas driven explosion or dual fuel explosion, however, few studies have investigated synergic explosion (i.e., the concentrations of both dust and gas are below the *MEC* or *LEL* of their pure substances in air). And less attention has been paid to the explosion sensitivity of hybrid mixtures, such as minimum ignition temperature/energy (*MIT*/*MIE*) and *MEC* etc. To fill this gap, this paper thus aims to study the *MEC* of hybrid coal dust-flammable gas mixtures in synergic explosion regions.

2. Experimental

2.1. Experimental materials

Methane, hydrogen and carbon monoxide were selected as the flammable gases. The properties of these flammable gases are shown in Table 1. Usually, the concentration in premixed 40-L gas cylinders is not the concentration of participating the reaction for the air existence in the test chamber and dust container, so we make some calculations as Eq. (1) and convert the concentration in the gas cylinder into the concentration of participating the reaction.

$$C_{\text{chamber}} = \frac{\Delta P_1 \times \Delta P_2}{P_1 \times P_2} \times C_{\text{cylinder}} \tag{1}$$

whereΔP_1 is the pressure difference before and after of compressed gas inject the dust container, P_1 is the pressure after the compressed gas inject the dust container, ΔP_2 is the pressure difference before and after the gas from the dust container to the chamber, P_2 is the pressure in the chamber before the ignite, C_{cylinder} is the mole fraction in the 40-L gas cylinder and C_{chmaber} is the mole fraction of participating the reaction in the explosion chamber. The concentrations of the flammable gases used in explosion chamber were calculated according to Eq. (1) as shown in Table 2.

Two coal dust samples with different volatile matters: anthracite coal and bituminous coal were used in this work. Prior to each test, the dust was systematically dried at 40 ℃ in a vacuum oven for 2 h. Table 3 shows the industrial analysis of the coal dusts including the compositions and the heat value. The particle size distribution also plays an important role in the explosion characteristics of dust clouds [25,26]. A particle size analyser equipment (CAM-SIZER) was used to examine size distribution of the coal dusts. Fig. 1 represents the size distributions of the coal dusts, showing that the median diameters are 9.95 and 14.33 μm for anthracite and bituminous coal, respectively. Moreover, the SEM (scanning election microscopy) images of these two coal dust samples illustrate that individual particles are not spherical but a granular shape (Fig. 2).

Table 2
Concentration of the flammable gases.

Concentration	CH_4			H_2			CO		
C_{cylinder} (vol. %)	1	2	3	1	2	2.5	1	2	3
C_{chamber} (vol. %)	0.57	1.14	1.71	0.57	1.14	1.43	0.57	1.14	1.71

2.2. Experimental apparatus and procedure

This section describes a standardized test sphere used to measure the explosion parameters as is shown Fig. 3. It consisted of a spherical test chamber with a volume of 20 L and a dust container with a volume of 0.6 L. A water jacket was made surrounding by the stainless-steel spherical chamber for the control of the internal wall temperature. The details of the apparatus can be referred from European Standards [27] and Krietsch et al. [25]. During the test, the pre-weighed coal dusts were settled down the dust container with a volume of 0.6 L, and then were dispersed into the 20-L spherical chamber that was evacuated to 0.4 bar with the help of premixed compressed gas mixture (21 bar) and ignited by a centrally-mounted chemical igniter with the energy of 10 kJ. Note that a fixed ignition delay time (i.e., the time interval from the beginning of air/gas mixtures blast to the moment of ignition) of 60 ms was used for all the tests in this work. Consequently, the explosion pressure was recorded as a function of time by using piezoelectric pressure sensors. All the tests were conducted 3 times and the average value was taken as the test results.

3. Methods of MEC determination

Two methods were used to determine *MEC* in the dust explosions: according to overpressure or combustion duration time of dust explosion. The most common one is based on the European Standard EN 14034 [27], i.e., an overpressure of 0.03 MPa excluding ignitor is regarded as the explosion/non-explosion criterion. In this work, 10-kJ chemical igniters were used which can can generate explosion pressure of 0.11 MPa, and 40 g/m^3 coal dust sample was used as the initial dust concentration. If the maximum pressure of the test was higher than 0.14 MPa (gauge), the concentration of coal dust was decreased by using 10 g/m^3 as the concentration gradient until the maximum pressure was lower than 0.14 MPa (gauge), and the corresponding concentration was defined as C_1. Then the concentration was increased by 5 g/m^3 as the concentration gradient until the maximum pressure was equal to or slightly higher than 0.14 MPa (gauge) with three repetitions, and the corresponding concentration was defined as C_2. Finally, the target concentration (C_t) was supposed to be between C_1 and C_2, i.e.,

Table 1
Properties of flammable gases [24].

Properties	Density (g/m^3)	Molecular weight	Explosible range (vol./%)	Specific heat capacity (kJ/kg·K)	Heat of combustion (kJ/mol)
CH_4	660	16	4.4–17	2.238	890.3
H_2	89.9	2	4–77	14.44	285.5
CO	1250	28	10.9–75.6	1.039	283.0