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Experimental study on the minimum ignition temperature of coal dust clouds in oxy-fuel combustion atmospheres

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HIGHLIGHTS

- MITC clearly decreases with increasing oxygen mole fraction.
- MITC in 21% O_2/79% CO_2 is slightly higher than that in air.
- A modified steady state heterogeneous ignition model is proposed to evaluate the ignition mechanism of coal dusts under the MITC conditions.
- Heterogeneous ignition dominates the ignition mechanism for sub-/bituminous coal dusts.

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ABSTRACT

BAM furnace apparatus tests were conducted to investigate the minimum ignition temperature of coal dusts (MITC) in O_2/CO_2 atmospheres with an O_2 mole fraction from 20 to 50%. Three coal dusts: Indonesian Sebuku coal, Pittsburgh No.8 coal and South African coal were tested. Experimental results showed that the dust explosion risk increases significantly with increasing O_2 mole fraction by reducing the minimum ignition temperature for the three tested coal dust clouds dramatically (even by 100 °C). Compared with conventional combustion, the inhibiting effect of CO_2 was found to be comparatively large in dust clouds, particularly for the coal dusts with high volatile content. The retardation effect of the moisture content on the ignition of dust clouds was also found to be pronounced. In addition, a modified steady-state mathematical model based on heterogeneous reaction was proposed to interpret the observed experimental phenomena and to estimate the ignition mechanism of coal dust clouds under minimum ignition temperature conditions. The analysis revealed that heterogeneous ignition dominates the ignition mechanism for sub-/bituminous coal dusts under minimum ignition temperature conditions, but the decrease of coal maturity facilitates homogeneous ignition. These results improve our understanding of the ignition behaviour and the explosion risk of coal dust clouds in oxy-fuel combustion atmospheres.

1. Introduction

Ignition of coal dust clouds is of interest in the fields of industrial safety, pulverized coal combustion, as well as a fundamental issue in combustion science and technology [1,2]. Studies of the ignition characteristics for both single particles and particle streams in oxy-fuel combustion conditions have drawn substantial attention in recent years due to their promising potential for reducing carbon emissions [3–9]. Instead of using air as the oxidizer, oxy-fuel combustion uses pure oxygen or a mixture of O_2 and recycled flue gas (mainly CO_2) to generate high-concentration CO_2 gas products for carbon capture and storage. The ignition of coal particles has been experimentally investigated by wire mesh reactor (WMR) [4], drop-tube furnace (DTF) [5–7] and thermogravimetric analysis (TGA) [8,9]. Qiao et al. [4] measured the ignition temperature of coal particles in both O_2/N_2 and O_2/CO_2 environments without the interference of volatiles burning and found that replacing air with a mixture of 21% O_2/79% CO_2 increases the average coal particle ignition temperature. Moreover, the average particle ignition temperature decreases with increasing O_2 concentration in the oxy-fuel combustion conditions. Khatami et al. [7] used a DTF with high-speed camera to examine the ignition delay and ignition mechanism for single coal particles. They [7] stated that increasing the oxygen mole fraction in either N_2 or CO_2 reduced the ignition delay mildly under quiescent gas conditions, while the ignition delay was dramatically prolonged in the slow-heating

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Nomenclature

A	Apparent pre-exponential factor, m/s
α	Empirical power index
d	Diameter, m
D	Diffusion coefficient, m^2/s
E_a	Apparent activation energy, kJ/mol
$f(X_{O_2})$	Dimensionless correction coefficient
$g(X_{O_2})$	Thermal conductivity ratio of O_2/CO_2 to air
ΔH_c	Heating value, J/kg
h_t	Heat transfer coefficient, W/m^2-K
M	Gas molecular weight, g/mol
N	Particle number
Nu	Nusselt number
p_0	Ambient pressure, Pa
Pr	Prandtl number
Q	Volumetric heat release rate, W/m^3
R	Ideal gas constant, J/mol-K
R	Correlation coefficient of fitting
R_e	Reynolds number
S	Effective surface, m^2
T	Temperature, K
X	Mole fraction of gas component
Y	Mass fraction of gas component
LOC	Limiting oxygen concentration
MITC	Minimum ignition temperature of dust cloud

Greek symbols

ρ	Density, kg/m^3
λ	Thermal conductivity, W/m-K
μ	Dynamic viscosity, kg/m-s
ν	Kinematic viscosity, m^2/s
φ	Function for O_2/CO_2 mixture viscosity

Subscripts

c	Coal
cl	Dust cloud
g	Gas
mci	Minimum ignition parameter of dust cloud
p	Coal particle

O_2/CO_2 atmospheres under an active gas flow condition. Wang et al. [9] found that the coal combustion process in a mixture of 30% O_2/70% CO_2 displayed no difference with combustion in air, which agrees with the findings of Molina and Shaddix [5].

Meanwhile, the ignition mechanism of coal particles has been studied both experimentally and theoretically, considering factors such as particle size [2,10], ambient temperature [11,12], oxygen mole fraction [12,13] and convection [7,13]. Zhang and Wall [2] developed a steady-state model to study the effects of particle size and ambient oxygen concentration on the ignition mechanism of dust clouds, and concluded that homogeneous ignition is more likely to occur at low oxygen concentrations, while heterogeneous ignition tends to occur at high oxygen concentrations. Then this model was successfully used to interpret the effect of particle size on minimum ignition temperature and ignition mechanism of sulphide dust clouds in the work of Amyotte et al. [10]. More recently, Ponzio et al. [12] developed a novel model to predict the ignition mechanism of single coal particles directly from the oxygen concentration and the oxidizer temperature, suggesting that flame ignition by homogeneous ignition of volatiles is more likely at low oxygen concentration and high oxidizer temperature, which is consistent with the observation of Zhang and Wall [2]. Liu et al. [13] found that the ignition mechanism of single bituminous coal particles with diameter of ~1.5 mm was conditionally changed by the convention and oxygen concentrations.

Table 1
Properties of the coal dust samples.

Properties	Coal dust samples		
	IS (Sub-bituminous) Dry (raw)	P8 (High-volatile bituminous) Dry (raw)	SA (Medium-volatile bituminous) Dry
Proximate analysis			
Fixed carbon (%) (by diff.)	47.0(43.9)	56(54.1)	56.3
Volatile matter (%)	38.2(35.8)	31.3(30.1)	26.9
Moisture content (%)	3.0(9.3)	2.2(5.7)	2.7
Ash (%)	11.8(11.0)	10.5(10.1)	14.1
Ultimate analysis (on a dry basis)			
Carbon (%)	65.7	73.8	67.5
Hydrogen (%)	5.22	4.82	4.26
Nitrogen (%)	1.58	1.29	1.76
Sulphur (%)	0.31(0.28)	0.83(0.79)	0.44
Ash (%)	10.6(9.8)	10.8(10.3)	14.9
Oxygen (%) (by diff.)	16.59(17.42)	8.64(9.18)	11.58
Gross heating value of dry fuel (MJ/kg)	27.65	29.78	27.37
Bulk density of dry fuel (kg/m^3)	645 ± 5	620 ± 5	600 ± 5

The aforementioned works mainly focused on the ignition characteristics such as ignition temperature and ignition delay of single coal particles in oxy-fuel atmospheres. However, less attention has been paid to critical ignition characteristics of dust clouds that are important for industrial safety [14–16]. In the oxy-fuel combustion system, neither the increased risk of fires and dust explosions with increasing oxygen mole fraction, nor the effect of enriched CO_2 on these risks has been well studied. Thus, knowledge of the fundamental ignition sensitivity characteristics is of importance for fire and dust explosion prevention in oxy-fuel combustion environments. Previous work in our laboratory experimentally investigated the fire risk posed by self-ignition of coal dust accumulations in oxy-fuel combustion systems [17]. This paper contains two main parts. Firstly, the experimental section is to determine the minimum ignition temperature (MITC or T_{mci}) of coal dust samples in air and O_2/CO_2 atmospheres. Considering that a hot surface is one of the most common ignition sources for dust cloud explosions, BAM furnace [10,18] tests are performed in this work. By varying the gas conditions and moisture content, the MITCs were determined. On the basis of those determined experimental data, the second section is to estimate the ignition mechanism of coal dust cloud samples under the MITC conditions via a proposed steady-state heterogeneous ignition model.

2. Experimental apparatus and procedure

2.1. Coal dust samples

Three different coals Indonesian Sebuku (IS) coal, Pittsburgh no.8 (P8) coal and South African (SA) coal were employed in this study. These samples were first milled or sieved in order to obtain dust particles with a diameter <63 μm, and then dried in a vacuum oven at 80 °C and pressure 0.1 bar until the moisture content was no more than 3% in mass basis. In order to determine the effect of moisture content (MC) on the critical ignition temperature, raw (i.e., not dried) dust samples of IS and P8 coals were also prepared. The particle size distributions of the prepared samples are very similar as can be seen in Fig. 1. The median values (d_{50}) of the particle size are 14.9 μm (IS coal), 11.8 μm (P8 coal) and 15.0 μm (SA coal), respectively. Table 1 shows the results of the proximate and ultimate analyses for these three coals. In general, the P8 and SA coals