



Experimental investigation on the self-ignition behaviour of coal dust accumulations in oxy-fuel combustion system



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HIGHLIGHTS

- Both critical ignition temperature and ignition delay time of coal dusts clearly decrease with increasing oxygen mole fraction.
- Critical ignition temperature in 21% O₂ + 79% CO₂ is slightly higher than that in air.
- A modified F-K analysis is proposed to evaluate the self-ignition risk of coal dust in the oxygen-enriched O₂/CO₂ ambient.
- Both the reactivity and sensitivity of oxidation decrease as the maturity of coal sample increases.

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ABSTRACT

For the oxy-coal combustion, the accumulation of coal dust in the system has a fire risk of self-ignition. Therefore, understanding the ignition dynamics of coal dust deposits in oxygen-enriched environment is essential for the prevention of fire and dust explosion. In this work, both hot-oven and hot-plate tests were conducted to study the self-ignition behaviour of coal dusts in O₂/CO₂ ambient with O₂ mole fraction from 21% to 50%. Three coal dusts: Indonesian Sebuk coal, Pittsburgh No. 8 coal and South African coal were tested with different sizes. Experimental results revealed that the self-ignition risk increased significantly with the increasing O₂ mole fraction: reducing both the critical ignition temperature (10 °C in hot-oven test and 40 °C in hot-plate test) and the ignition delay time. Comparatively, the inhibiting effect of CO₂ was found to be small for self-ignition. In addition, a modified Frank-Kamenetzki analysis was proposed to explain all measured critical ignition temperatures, and the genetic algorithm was used to determine kinetic parameters of the one-step global reaction. The analysis showed that as the coal maturity/rank increased, both the self-ignition risk and the sensitivity to oxidation decreased, along with the decreasing apparent activation energy and pre-exponential factor. Such trend did not change with the ambient oxygen condition for all three coal dusts. These results improve our understanding of the self-ignition behaviour and the fire risk of coal dust in the oxy-fuel combustion system.

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1. Introduction

Coal has been and will continue to be one of the main energy resources in the long term because of its abundant reserves and competitively low price [1]. However, coal combustion has the highest specific carbon emission compared to other fossil fuels. In recent years, oxy-fuel combustion with carbon storage, is one of the most promising technologies for reducing carbon dioxide

(CO₂) emissions from the coal-fired power generation, and has been developed and advanced [1,2]. Instead of using air as the oxidizer, oxy-fuel combustion uses pure oxygen (O₂) or a mixture of O₂ and recycled flue gas (mainly CO₂) to generate high-concentration CO₂ gas products for carbon storage [1–4]. However, the fire safety and explosion risk for a combustion system in oxygen-enriched environments is a major technological challenge that has not been well studied. Dust accumulation often occurs in the coal mills and power plants. Once in touch with the oxidant and a mild heat source, the accumulated dust may self-heat to initiate the smouldering combustion [5–7]. Moreover, self-ignition or the subsequent

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Nomenclature

A	pre-exponential factor, 1/s
Bi	Biot number
C	molar concentration, mol/m ³
d	internal diameter of ring, m
D	diffusion coefficient, m ² /s
E_a	apparent activation energy, kJ/mol
f	reaction model in solid phase
g	gravitational constant, m/s ²
$g(C_{O_2})$	oxidation model
h_c	convective coefficient, W/m ² K
ΔH_c	heating value, MJ/kg
k	thermal conductivity, W/m K
L	thickness of dust layer, m
n	reaction order
\dot{Q}	volumetric heat release rate, W/m ³
r_o	characteristic length, m
R	ideal gas constant, J/mol K
t	time, s
t_i	ignition delay time, s
T	temperature, K
X	mole fraction of gas component
Y	mass fraction of gas component
MIT	minimum ignition temperature
SIT	self-ignition temperature

Greek symbols

α	thermal diffusivity, m ² /s
β	inverse film temperature, 1/K
δ	Frank-Kamenetskii parameter
ε	emissivity
ν	kinematic viscosity of air, m ² /s
ν	stoichiometric coefficient
ρ	density, kg/m ³
σ	Stefan–Boltzmann constant, W/m ² K ⁴
$\dot{\omega}$	normalized reaction rate, 1/s

Subscripts

0	central of basket
a	ambient
c	coal
cr	critical
g	gas
i	species
ig	ignition
max	maximum or peak
p	hot plate
r	residue
s	upper surface of dust layer

smouldering can act directly as an ignition source or indirectly by means of agglomerations or ‘nests’ of burning material that break away from deposits inducing fires and explosions [5,8,9]. All these risks may vary in the CO₂-abundant ambient and further increase in the oxygen-enriched ambient.

The self-heating and self-ignition behaviours of fuels are often experimentally investigated with hot-oven [10–14], hot-plate [15–18], thermogravimetric (TG) and differential scanning calorimetric (DSC) [19,20] tests. Various effects on self-ignition have been investigated in air, such as fuel particle size [20], composition [11], moisture [14], shrinkage [15], and inert matters [16]. Since the self-ignition is initiated by smouldering combustion, it strongly depends on the oxidation rate and the oxygen diffusion process into the porous dust [5,21,22]. Bowes and Thomas [10] and Schmidt et al. [12] both found that for the O₂ mole fractions lower than 30% in nitrogen (N₂), the fuel self-ignition temperature decreased with increasing O₂ mole fraction [10,12]. Wang et al. [23] found that the TG curve of coal dust in 30% O₂/70% CO₂ was similar to that in air. Qiao et al. [24] measured the ignition temperatures of coal dust in a mesh reactor under various gas compositions, and found the influence of CO₂ was much smaller than that of O₂ mole fraction. Chen et al. [25] reviewed recent studies on oxy-fuel combustion where the ignition and flame temperatures in O₂/CO₂ ambient with O₂ mole fractions of 25–35% were found to be similar to those in air. By far, neither the self-ignition of coal dust in the O₂-rich ambient nor in the O₂/CO₂ ambient has not been studied in bench-scale experiments.

In this paper, we experimentally studied the self-ignition behaviour of three coal dusts through both hot-oven and hot-plate tests in air and various O₂/CO₂ ambient. By varying the gas composition and heating condition, we determined and compared the critical ignition temperature, ignition delay, and kinetic parameters of three coal dusts. The aim of this study is to improve the fundamental understanding of low-temperature oxidation and self-ignition behaviour of coal dusts, especially in oxy-fuel combustion system.

2. Experimental methods

2.1. Experimental samples and gas compositions

Three different coals: South African (SA) coal, Indonesian Sebuk (IS) coal, and Pittsburgh No.8 (P8) coal were investigated in this study. These coal samples were first milled or sieved into dust diameter < 63 μm, and then dried in an oven at 80 °C and 1 atm until the maximum moisture content was less than 3% in the mass basis. Table 1 shows the results of proximate and ultimate analyses for these three coals. In general, the P8 and SA coals have clearly higher fixed carbon and lower volatile compounds (*i.e.* more mature or rank higher) than the IS coal. At the same time, their ash contents, bulk densities, and heating values are similar. In experiment, air and O₂/CO₂ mixtures with various O₂ mole (or volume) fractions, X_{O₂} = 21, 30, 40 and 50 ± 1%, at 1 atm were used as ambient gases.

Table 1
Properties of the coal dust samples.

Properties	Coal dust samples		
	IS	P8	SA
<i>Proximate analysis (wt.%)</i>			
Fixed carbon	47	55.6	56.6
Volatile compounds	38.2	31	27.1
Moisture content	3	3	2.1
Ash	11.8	10.4	14.2
<i>Ultimate analysis (%)</i>			
Carbon	65.7	73.8	67.5
Hydrogen	5.22	4.82	4.26
Nitrogen	1.58	1.29	1.76
Oxygen	27.5	20.09	26.48
Heating value (MJ/kg)	27.65	29.78	27.37
Bulk density (kg/m ³)	645 ± 5	620 ± 5	600 ± 5

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