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Full Length Article

Comparative ignition tests of coal under oxy-fuel conditions in a standardized laboratory test rig

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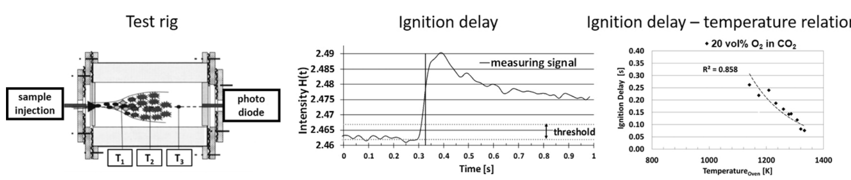
HIGHLIGHTS

- Good compromise between informative power and simple and reproducible processing.
- Tendencies known for the influence of O_2-concentration and coal rank are shown.
- Higher O_2-concentration in the atmosphere lead to lower ignition temperature.
- Higher volatile content in coal generally lead to lower ignition temperature.
- Conversion of this simple method to oxy-fuel environments has been successful.

GRAPHICAL ABSTRACT



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ABSTRACT

Ignitability is important to characterize pulverized coal combustion, as it is directly related to flame stability. The current work describes a practical test rig for rapid laboratory analysis of pulverized coal cloud ignition properties. The system has been designed for conventional coal combustion conditions using air as the oxidant. In the current work, the measurement principle of the device is described and its adaption to and applicability for oxy-fuel combustion tests is demonstrated. Four coals with different rank were measured in air and in oxy-fuel atmospheres containing 20–35 vol% O_2 in CO_2. The major influencing factors for the investigated samples were found to be the coal rank and the gas-phase oxygen concentration, while a minor influence of particle size was observed.

1. Introduction

Coal combustion under oxy-fuel conditions is a promising option to reduce carbon dioxide emissions by facilitating carbon capture and sequestration [1,2]. Because of the extremely high combustion temperatures in undiluted oxy-fuel combustion, leading to excessive melting and vaporization of ash in coal, oxy-fuel combustion of coal is typically conducted with dilution of the oxygen with recycled fuel gas. Compared to conventional (air-fired) systems, the high content of CO_2 in the recirculated flue gas is known to change the combustion process significantly [1]. The change in gas properties such as thermal conductivity, heat capacity and diffusivity of oxygen affects ignition properties, flame temperature, and flame stability under oxy-fuel conditions [3]. Previous investigations have shown that higher oxygen concentrations (25–30 vol%) are needed

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to reach combustion properties comparable to air-fired pulverized coal (pc) systems [2]. However, the higher oxygen content was identified to be of potential risk for auto-ignition of deposited coal dust in coal feed lines, a typical problem for pulverized fuels [4,5], which led to a series of laboratory tests directed at this specific problem [6,7].

There have been a number of previous studies on pulverized fuel ignition. An early review on group ignition experiments was presented by Essenhigh et al. [8]. Wall et al. summarized experiments focusing on the minimum ignition temperature of coal particles [9]. The phenomena of the ignition of a particle stream were described and analyzed by Annamalai and coworkers [10,11]. A review of the effects dominating the combustion process of coal particle clouds is given [11]. While many different techniques were utilized, most involve drop-tube reactor (DTR) or entrained flow reactor (EFR) experiments. The ignition temperature of seven coals with varying rank was tested in an EFR by Faúndez et al. [12]. There, coal particles sieved to 53–106 μm were fed to the reactor with a feed rate of 0.5 g/min, simulating group ignition, while the reactor temperature was increased by 15 °C/min until the gas concentration, i.e. rising concentrations on CO, CO_2 and NO with simultaneous decrease in O_2, indicated ignition. Decreasing coal rank and increasing excess O_2 caused a decrease in the apparent ignition temperature T_{ign}. Additional TGA experiments confirmed the tendencies from the EFR, but the ignition temperature was slightly lower. Zhang and coworkers presented further TGA results, but the typically low heating rates in this type of experiments is a mismatch to pc conditions [13]. Other groups studied the ignition of single coal particles [14–17] or particle group ignition [18,19] by image based techniques. Molina and Shaddix used an EFR to study the ignition of single coal particles in N_2 and CO_2 dominated atmospheres with 21 and 30 vol% O_2 [14]. They measured CH^* chemiluminescence and thermal radiation from the soot cloud enveloping igniting particles using an very sensitive CCD camera and found that the ignition in CO_2 is delayed, but the duration of pyrolysis is comparable to N_2 conditions. The same authors extended their studies and investigated the high temperature soot cloud around igniting particles with a wider variation of O_2 concentrations, finding O_2 to accelerate the devolatilization process and to change the shape of the soot cloud surrounding ignited particles. Two reasons potentially contribute to the delayed ignition in oxy-fuel atmospheres: the high heat capacity of CO_2 and the tendency for CO_2 to suppress radical formation. Schiemann et al. investigated the ignition of single coal particles in atmospheres with low O_2 content (4–10 vol%) [16]. With a CO_2 diluent a higher O_2 concentration is necessary for similar devolatilization compared to a N_2 diluent. Another image analysis based approach for single particle ignition experiments was presented by Magalhães et al. [17], where coal and biomass particles were examined with respect to their apparent ignition mode. Drop tube experiments on coal particle ignition were described using high speed cinematography and a ratio pyrometer to determine ignition times and ignition modes for coals of different rank in different CO_2- and N_2-based atmospheres [20,21]. In previous work ignition in quiescent and flowing atmospheres was compared, and the ignition in quiescent CO_2/O_2 was slow compared to all other conditions [20]. The ignition criterion applied by Riaza and coworkers is based on the luminous intensity recorded with a ratio pyrometer [21]. When ignition of a particle in the reactor occurred, the maximum gradient of the luminosity was chosen as the characteristic time of ignition. Supported by high-speed cinematography, the apparent ignition mode was determined for coals of different rank under varying conditions. All work considered has in common that it focuses either on group ignition at low particle concentrations or on single particle ignition. The ignition times reported are quite short, in the range of 10–30 ms, depending on the conditions, which is not typical for pc combustion, where the high coal particle concentration in the carrier gas flow at the burner leads to pronounced group combustion phenomena.

Liu et al. studied the ignition of coal particle streams with respect to the particle number density [18]. They used similar chemiluminescence and thermal radiation measurements [14]. A minimum in the ignition delay time was found at particle number densities around $4 \times 10^9/m^3$. The general tendencies regarding increasing ignition delay with increasing particle size, coal rank and substitution of N_2 by CO_2 were confirmed. Based on a particle spacing ratio (av. distance between particles) for pc injection conditions, Yuan et al. concluded that the ignition of particle clouds is the statistical sum of single particle ignitions [19]. The major purpose of their investigation is the differentiation between heterogeneous and homogeneous ignition with respect to the boundary conditions. Work on the influence of steam on pulverized coal was recently performed, which concludes that the addition of steam in oxy-fuel-ignition tests triggers water-gas shift reactions which promote ignition [22,23].

The literature dealing with coal ignition in lab-scale furnaces clearly states tendencies regarding delayed ignition with increasing coal rank and particle size, decreasing oxygen content, and substitution of N_2 by CO_2. Except from Faúndez et al. [12] and Prationo et al. [23], all work uses gas temperatures above 1200 K. The oxygen content is relatively high (above 10 vol%, except [16,17]), as these oxygen concentrations are suggested for stabilizing the flame in oxy-fuel combustion. The conditions used in the cited literature are summarized in Table 1.

Although the literature gives valuable insight into ignition, especially into ignition modes and single particle ignition, they are related to specific experimental setups and require explicit knowledge for the interpretation of the results.

The current work presents a technique which has been suggested by Zelkowski [24] as a laboratory standard. The design proposes a specific furnace. The basic idea behind the Zelkowski [24] method is to define an ignition temperature which is in accordance with typical time scales in industrial firing systems. Therefore, the definition is – based on experience with boiler operation – that flame stand-off distances should not exceed 3 m downstream of the burner mouth. For typical flow velocities of 20 m/s this leads to a required ignition delay of 150 ms. Therefore, the characteristic ignition temperature T_{Zel} is postulated to be equal to the furnace temperature in which ignition of a fuel dust cloud takes place 0.15 s after sample insertion under air-fired conditions. If other flow velocity or stand-off distances are of interest because of varying burner design the ignition delay time has to be adapted accordingly.

The Zelkowski analysis is used as a first indicator of coal combustion characteristics within Uniper Technologies GmbH fuel laboratory. It provides a quick test, which gives a first "fingerprint" for the ignition characterization of pulverized fuels. It has been proven to give valuable information about the ignition characteristics in case of alternating fuel supplies and reflects the operation experience of Uniper Technologies GmbH with boilers from different manufacturers.

Oxy-fuel conditions need further consideration of the oxygen content, which is in practice adjusted by the O_2 feed rate and the recirculation rate of CO_2. As a consequence, the Zelkowski method of ignition testing has been adapted to oxy-fuel requirements by adding a variable CO_2/O_2 supply to the conventional test rig. Four typical coals with varying rank, which are utilized in pc power plants, were tested in the Zelkowski setup with air and varying oxygen concentrations in CO_2 to evaluate the ignition time-temperature relationship.