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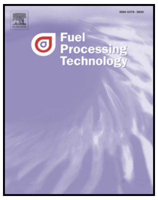

Research article

Clarifying the influence of moisture on the ignition and combustion of wet Victorian brown coal in air-firing and oxy-fuel modes: Part 2: Contribution of gasification reaction to char oxidation rate

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ABSTRACT

This paper is the second part of the study to clarify the influence of moisture in Victorian brown coal oxy-fuel combustion, with a focus on char oxidation and gasification reaction through experimental and modelling efforts. An in-situ high-speed two-colour pyrometer with the wavelength band of 0.85–1.05 μm was employed to measure particle temperature in the flat flame burner reactor. The combustion stage of carbon particle was simulated for the transient phenomena with particle heating and radiative heat transfer. The multiple surface reaction single-film approach, including char–O_2, char–CO_2 and char–steam reactions, was employed and the contribution of individual reactions to carbon consumption rate was determined via matching with the measured particle temperature. Irrespective of the initial moisture content, the extent of char–steam gasification reaction was found to account for ~15% in the air-firing case. This reaction was mainly triggered by the external steam in the reactor, rather than the inherent moisture that resided preferentially as volatile cloud on char particle surface. The combined effect of both char–CO_2 and char–steam gasification was significant in oxy-fuel combustion mode, especially for the wet coal. In the oxy-21 case, these two reactions have a total extent of around 8% and 18% on the burning char surface of dried and wet coal, respectively. The char–CO_2 gasification is insignificant, because the char particle temperature was low. Increasing the oxygen percentage to 31% in CO_2 enhanced the total extent of these two gasification reactions to 28%, based on the mass of total carbon. Such an extent is comparable with the literature. However, the steam gasification rate for brown coal char was far higher, ~26% relative to ~10% for high-rank bituminous coal reported in the literature. This substantiates the strong steam gasification reactivity of Victorian brown coal char. The contribution of inherent moisture to char–steam gasification reaction is crucial in the combustion of wet coal in the oxy-21 case, accounting for ~10%. This is due to the long residence of the unevaporated steam as a thick cloud on the char surface. Increasing the oxygen concentration in CO_2 enhanced the char–O_2 reaction, the release rate of volatiles and inherent moisture. Therefore, the char–steam reaction caused by the inherent moisture within coal matrix was minimised and eventually diminished in the oxy-31 case.

1. Introduction

Oxy-fuel combustion is a promising low-emission technology that can be implemented in the short term to mitigate the carbon dioxide emitted from the stationary power plants. To date, most of the investigations focused on the combustion on high-rank bituminous coals [1–6]. The test of Victorian brown coal, which is abundant in moisture [7], in oxy-fuel mode generates abundant steam in the furnace, due to the recirculation of flue gas. Wall et al. has pointed the necessity of the investigation of steam dilution in oxy-firing furnace [8]. In our previous lab-scale drop-tube furnace (DTF) study on wet coal combustion, the reduction on the temperature of burning wet coal particle has been witnessed, which was supposedly caused by the contribution of steam gasification reaction towards the char matrix as opposed to the steam gasification from the ambiance steam [9]. In contrast, another study on brown coal (~10%–60% moisture) in fluidised bed showed no change on the char oxidation regime with increasing the moisture content in brown coal, as the moisture has been suggested to fully evaporate prior to the beginning of the release of volatiles [10]. A clear and generalised view on the oxy-firing of Victorian brown coal has not yet been reached.

Numerous approaches on the CFD modelling have been conducted for coal oxy-fuel combustion [11,12]. Our previous modelling works has successfully utilised multiple reaction model, including char–O_2, char–CO_2 and char–steam in the CFD to predict the brown coal burning

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temperature profile and carbon burnout in a drop-tube furnace [13]. One-dimensional modelling approach using SKIPPY (Surface Kinetics in Porous Particles) has also successfully clarified the effect of CO_2 and steam gasification reaction on the oxidation of bituminous coal char [14,15]. These modelling approaches utilised traditional combustion model where coal is assumed to be completely dried prior to ignition and there is no overlapping of individual steps including moisture evaporation and volatile release/ignition. Clearly, this is not the case for the oxy-firing of wet Victorian brown coal that has been observed in flat flame burner reactor [16] and in drop-tube furnace [9].

This paper is the second part of the study on wet Victorian brown coal combustion in flat flame burner reactor that employs a similar heating rate with the industrial boiler [16]. Complementing to the first part focusing on the ignition and volatile oxidation, this paper aims to assess whether the inherent moisture affects char oxidation rate and particle temperature through char–steam gasification reaction. As has been clarified in the first part, the inherent moisture is only partially evaporated prior to volatile ignition; whereas the remaining moisture and volatiles are co-released as a thick could layer on the char surface, which is supposed to increase the local steam partial pressure and hence trigger the char–steam gasification reaction. This is different from the previous studies in the literature where only the external steam in flue gas has been considered.

2. Experimental set-up

2.1. High-speed infrared pyrometer for coal particle temperature measurement

The coal samples and the flat flame burner reactor (FFBR) for coal combustion have been detailed in part 1 [16]. For char particle temperature measurement, a Kleiber-GmbH high-speed infrared pyrometer KS-740 LO was installed next to the observation window along the quartz reactor on the FFBR. The pyrometer captured signal at the rate of 5 MHz with the linear voltage output of 0–10 V. It has the capability of measuring the surface temperature in the range of 1073–2573 K. The pyrometer is operated at the wavelength between 0.85 μm and 1.05 μm to avoid the interference of the CO_2 and water vapour [17], which are abundant in oxy-fuel atmosphere. The emissivity of the pyrometer was adjusted to 0.8, based on the suggestion from Baum [18]. The data was captured using an oscilloscope and data acquisition instrument. The measurements were taken at the reactor height of 50 mm and 75 mm above the burner base. These two distances chosen refer to char oxidation stage with the first distance 50 mm for the simultaneous volatile and char oxidation and the second distance 75 mm for char oxidation alone.

3. Mathematical model

The modelling of single coal particle combustion here was modified based on the previous model described in the literature [13,18]. The code employed only focused on one-dimensional transient calculations. The gas mixture properties, including thermal conductivity, heat capacity, viscosity and density was calculated using the Wilke's Mixture rule and Maxon–Saxena formulation, corresponding to the statistical collision theory [19].

3.1. Modelling approach

Coal particles undergo rapid heating once being introduced to the furnace. The heat transferred to particle is driven by the convection from hot gas and radiation from the surrounding volatile flame as well as radiation from the furnace wall, which has the potential to increase particle temperature in the magnitude of ~10^5 K/s. The transient model of single spherical coal particle with a diameter d_p, immersed in the hot gas of temperature T_g, was used to simulate its combustion behaviour. The following sub-models were applied in sequence, drying model, devolatilisation model and finally char oxidation model. The former two have been detailed in part 1 [16], whereas the last one is detailed below.

3.1.1. Char oxidation model

The three heterogeneous char surface reactions, as listed in Reactions (I)–(III) were assumed to occur with first-order global Arrhenius rates.

$$C + 1/2O_2 \rightarrow CO/CO_2 \tag{I}$$

$$C + CO_2 \rightarrow 2CO \tag{II}$$

$$C + H_2O \rightarrow CO + H_2. \tag{III}$$

The rate of char burning is described using the multiple surface reactions' kinetic-diffusion single-film approach, assuming that the above-listed multiple reactions occur in a frozen boundary layer at the particle surface with no gas-phase reactions. This model has been proven to work satisfactorily for the combustion of pulverised coal less than 100 μm in diameter [20]. For the combustion of particles larger than 100 μm, Mitchell suggested that the conversion of CO to CO_2 in boundary layer is non-negligible [21]. It has also been postulated by Law that the characteristics diffusion time is normally negligible for the droplets less than 100 μm in diameter [22]. In other words, the droplets less than 100 μm in diameter are too small to support the existence of a gaseous flame on its surface. Therefore, it is safe to assume that the frozen boundary layer assumption can be used in this numerical study. The char combustion rate can be written as:

$$q = \frac{P_{O_2}}{\frac{1}{k_{c,o}} + \frac{1}{k_{d,o}}} + \frac{P_{CO_2}}{\frac{1}{k_{c,c}} + \frac{1}{k_{d,c}}} + \frac{P_{H_2O}}{\frac{1}{k_{c,s}} + \frac{1}{k_{d,s}}} \tag{1}$$

$$k_c = A \ \exp\left(-\frac{E}{RT}\right) \tag{2}$$

$$k_d = C_2 \frac{\left(\frac{T_p + T_\infty}{2}\right)^{0.75}}{d_p} \tag{3}$$

$$\frac{\partial d}{\partial t} = -\frac{2q}{\rho}. \tag{4}$$

With k_c and k_d are chemical reaction rate coefficient and diffusion reaction rate coefficient, respectively. The chemical reaction rate coefficient is expressed in an Arrhenius form with A being the pre-exponential factor and E as the activation energy for Reactions (I)–(III). The intrinsic kinetic parameters for Reactions (I)–(III) are obtained from thermo-gravimetric analyser (TGA) measurement. For Reactions (I) and (II), the TGA experiments were conducted at different heating rates (10–50 K/min) for devolatilised char in both air and pure CO_2 (grade 5) atmosphere, which have proven accurate in our previous work [13,23,24].

For the char–steam gasification Reaction (III), it is considered to include two reactions for wet coal combustion, one being induced by the external steam in bulk gas, and another one occurring within char matrix that is triggered by the internal moisture remaining 'permanently' after volatile ignition and those produced from the pyrolysis of coal. Due to the abundance of hydrogen and oxygen, Victorian brown coal pyrolysis results in the yield of 5–15 wt.% steam in the products [25]. Such a steam is non-distinguishable from the remaining moisture after the drying stage. The kinetic parameters for steam gasification

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