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The transition of heterogeneous–homogeneous ignitions of dispersed coal particle streams

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ABSTRACT

This work is assessing a study of the *collective* ignition behaviors of dispersed coal particle streams, with ambience temperature from 1200 K to 1800 K and oxygen mole fractions in the range of 10–30%. The dispersed coal particles of 65–74 μm are injected into an optical Hencken flat-flame burner by a novel de-agglomeration feeder. Three kinds of pulverized coals from different ranks, Hulunbel lignite, high-ash-fusion bituminous and low-ash-fusion bituminous, are considered. The normalized visible light signal intensity, deleting the background noise, is established to characterize the ignition delay of coal particle streams. Firstly, the prevalent transition from heterogeneous ignition to hetero–homogeneous ignition due to ambience temperature is observed. The pure homogeneous ignition rarely occurs, with an exception under high temperature and low oxygen for high-volatile coal. By comparing time scales between pyrolysis and heating processes, the competition of the volatile evolution and heterogeneous surface reaction are discussed. Then, the effects of ambience temperature, oxygen mole fraction and coal rank on the characteristic ignition delay are examined. Finally, the transient mode is developed, which not only well interprets the observed ignition transition phenomena, but also approximately predicts a variation of heterogeneous ignition time as a function of oxygen fraction.

1. Introduction

Studies on the ignition of isolated coal particles, in particular the particle streams around equivalence conditions, have aroused substantial and renewed attention due to technological needs and it is still an unsolved problem in the combustion community. In the past several decades, there have been dozens of extensive researches on the ignition of either isolated particles [1–7] or particle streams and clouds [8–12]. However, the interplays between those two kinds of cases are scarcely discussed.

The simple stoichiometric and geometrical analysis on the pulverized coal particle stream is helpful to understand its relations with isolated particles. For example, 1 g/min standard bituminous coal ($\rho_p = 1300$ kg/m^3) approximately corresponds to 7 slpm (standard liter per minute) air under a stoichiometric condition, which enables the particle volume fraction c to be about 1.1×10^{-4} at room temperature and then about 3.0×10^{-5} at 1000 K. Assuming that the particle suspension is nearly mono-disperse around a mean size $\bar{d}_p$, the particle spacing ratios, $\ell/\bar{d}_p$, are estimated as 16.8 and 25.9 at 273 K and 1000 K, respectively, by applying a formula of $\ell/\bar{d}_p = (\pi/6c)^{1/3}$. The large particle spacing ratio implies that the ignition of coal particle streams can be regarded as a statistical summation of ignitions of all isolated particles under a well-dispersed condition. Otherwise, if these fed particles are agglomerated due to the molecular adhesions [13], the ignition mechanisms may involve the contributions of both isolated particles and interactive particle agglomerates. Naturally, the $\ell/\bar{d}_p$ between a particle agglomerate to the other one will become much higher than that between two isolated particles. The unclear degree of the agglomeration, including the number of primary particles and the fractal morphology, makes the ignition process more complicated. It is of great interest to develop a simply *well-dispersed* coal particle stream system for studying the ignition mechanisms of particle streams.

First, a brief review is given for the previous studies on the ignition mechanisms of a single (isolated) particle burning in air. For quite a long time, researchers speculated on whether pulverized coal particles experience a homogeneous gas-phase ignition (GI) or heterogeneous ignition (HI) mechanisms [1–5,14–16]. The former refers to a gas-phase ignition of pyrolytic vapors from coal that is similar to oil drop ignition, whereas the latter represents the direct oxidation of char and in-situ volatiles at the particle surface.

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Nomenclature

T	temperature (K)
r	radial distance from the particle center (m)
t	times (s)
C	specific heat (J/kg K)
σ	Stefan–Boltzmann constant (w/m^2 K^4)
ρ	density (kg/m^3)
V	volume (m^3)
A	surface area (m^2)
ε	emissivity
h	coefficient for convection heat transfer (W/m^2 K)
h_c	heating value for heterogeneous coal combustion (J/kg)
h_v	heating value for volatile decomposition (J/kg)
$\dot{M}_c$	carbon loss rate (kg/s)
$\dot{M}_v$	volatile loss rate (kg/s)
$\dot{m}$	mass flow rate (kg/s)
$\dot{w}'''_m$	volumetric gas phase mass source (kg/m^3 s)
$\dot{w}'''_h$	volumetric gas phase enthalpy source (W/m^3)
h_T	thermal enthalpy (J/kg)
m	mass (kg)
A	preexponential factor
E	activation energy (J/mol)
Y_k	species mass fraction
D	diffusion coefficient (m^2/s)
R	universal gas constant (J/mol K)

Subscript

w	surface of the particle
p	particle phase
gas	gas phase
V	volatiles
C	carbon, char
Vu	undevolatilized volatile

One of earliest recognized researches is done by de Soete to map both GI and HI modes using two significant parameters, e.g., particle diameter as the abscissa and heating rate as the ordinate [17]. It roughly clarified that GI mode usually occur for large particles under slow heating rates (e.g. <100 K/s), whereas HI mode is suitable for small particles (less than 100 μm) under high heating rates. Several experiments confirmed this HI mode by a case of bituminous coal particle with a size less than 65 μm [2,3] and also those of other kinds of coal such as anthracite, bituminous and its derived char [14]. The existing ignition techniques include drop-tube furnace (DTF) with pulse coal feeding (*pulse ignition*) or DTF with continuous coal feeding (*continuous flow ignition*), thermogravimetric analysis (TGA), wire-mesh reactor (WMR), and laser-induced ignition apparatus [18–22]. The ignition characteristics measured by the experimental techniques above are really different, due to quite distinct heating rates, reactor type, reaction mechanism, etc.

Among them, the drop tube furnaces (DTF) or the flat-flame burner (also known as one kind of entrained flow reactors) are considered to be much more appropriate devices for laboratory ignition studies. Firstly, the ultra-high heating rates in the order of 10^5 K/s in these devices can reproduce conditions suitable to those in practical systems. Secondly, more previous coal ignition studies, e.g., by TGA, have focused on the minimum ignition temperature (MIT), instead of residence time. For needs of flame stabilization of coal burner, people care how long it takes the coal particles to devolatilize and ignite in the hot environment into which they are introduced (termed as ignition delay), not what is the minimum steady state temperature for ignition. Early DTF studies determine the ignition event by the mass loss percentage of carbon and volatiles during the early moments of burning [2,3]. The optical diagnostics, e.g., photomultiplier, photo-detector and video camera, have received more attentions for determining the ignition mode of a particle based on its luminosity and size during the early moments of burning. For instance, the optical access of drop tube furnaces enabled the measurement of the temperature–time–size histories of individual coal particle by three-color pyrometry and high-speed high-resolution cinematography [6,7]. It was directly observed from the cinematography that the high-rank bituminous coal particles ignited homogeneously (GI mode) in either O_2/N_2 or O_2/CO_2 ambiences, while low-rank lignite coal particles experienced extensive bulk fragmentation and heterogeneous ignition. More importantly, by using optical techniques, the particle's ignition delay in DTF, defined as the time lapsing from the instant when the particle exited the injector to the onset of its luminous combustion, was studied under various conditions such as coal rank, oxygen mole fraction, and gas conditions. In a contrast to DTF, the Hencken-type flat-flame burner, using the inside high-temperature post-combustion gas flow as a heat source instead of the outside electrically-heated source, makes it more flexibly feasible for the optical diagnostics of the ignition delay of coal particles in gas streams. Evidently, the flow and heating conditions of fuel particles in the Hencken burner are much closer to the engineering practice than that in DTF. Shaddix and co-workers studied the ignition and devolatilization characteristics of both a high-volatile bituminous coal and a subbituminous coal through single-particle imaging at a gas temperature of 1700 K over a range of 12–36 vol% O_2 in both N_2 and CO_2 diluent gases [11,12]. They also compared the ignitions between high-rank bituminous coals and low-rank subbituminous coals similar to those done by DTF [6,7]. It was observed that the ignition of the bituminous coal can be characterized by the formation of a high-temperature soot cloud around coal particle. However, this cloud became indistinct during ignition of subbituminous coal. Although Hencken burner exhibits a promising prospective for direct optical studies on coal ignition delay, their interpretation with the theoretical ignition models, either GI or HI, are still quite scarce. Moreover, the operation of Hencken burner relies on a continuous steady-state feeding system for coal particles under well-dispersed conditions mentioned above. So far, to our best knowledge, this problem is yet not well solved. Thus, till now, the application of Hencken burner for ignition delay study, either GI or HI modes, is greatly less than that of DTFs under quiescent or inactive gas conditions.

Meanwhile, several theoretical models were developed for helping to interpret the ignition mechanisms of coal particles [1–5]. In particular, a theory on the transition of ignition between HI and GI modes was proposed by Annamalai and Durbetaki [5], showing their advantage for well explaining the effects of ambient temperatures, coal particle sizes, volatile matter contents, kinetic parameters, etc. [1]. However, the basic assumption of purely spherical particles in these models for both HI and GI modes differs greatly from coal fuel particles in practice. It implies that so far the clarifying on the ignition mechanism of coal particles still significantly relies on the improvement of more precise experiment system, coupled with the supplement of theoretical concepts cast in testable form.

In this paper, we aim to study the transition of heterogeneous–homogeneous ignitions of coal particle streams by developing an