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An overview of coal rank influence on ignition and combustion phenomena at the particle level

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ABSTRACT

Individual particles of pulverized coals exhibit strikingly different combustion phenomena depending on their rank (anthracite, semi-anthracite, bituminous, sub-bituminous and lignite). Herein a concise review is presented on pertinent findings in the literature to contrast ignition and combustion behavior of such fuels at the *particle-level*. Emphasis is given to recent investigations performed in the laboratory of the authors, where combustion of a variety of coal particles of the same size-cut took place in the same apparatus under identical operating conditions. Such behaviors were then compared to those reported in the literature to verify their replication under often different, but yet relevant, conditions. The objective has been to relate the effect of coal rank to a number of key qualitative and quantitative parameters, such as modes of ignition and combustion, ignition temperatures, ignition delay times, combustion temperatures and burnout times (both those encountered in the volatile and the char combustion phases), volatile flame sizes as well as extents of particle fragmentation. Besides reviewing combustion behaviors in air, analogous behaviors under simulated dry oxy-combustion conditions were also highlighted. Then the coal rank dependence of the required oxygen mole fraction in dry O_2/CO_2 blends to match the intensity of air-fired combustion was examined.

1. Introduction

Coal has been traditionally used to supply a great deal of the world's electric power generation needs. In recent years, approximately 40% of the world's electricity is generated by burning coal [1], and it has been projected that the global utilization of coal will continue in the foreseeable future as it is "abundant and cheap" [1–3]. This is particularly true for South Africa, China, Poland, Australia, India and other countries where more than two thirds of their electricity is currently generated from burning coal [4]. While global utilization of coal is increasing, in some countries usage for power generation has been declining in recent years. This is due to the competition from plentiful, low-priced and much cleaner-burning natural gas, as a result of rapid development of extraction techniques involving hydraulic fracturing ("fracking") in shale formations. However, a relevant opinion article [5] pointed out that the supply of affordable natural gas in the US has a finite lifetime and, as the price of natural gas increases in the future, the use of coal will rebound again, particularly if "clean-coal technologies", such as capture and sequestration of global CO_2 emissions (CCS), are proven and implemented [5].

To promote clean coal utilization, it is also important to improve the performance and efficiency of boilers and associated devices. To this end, a thorough understanding is needed of the combustion behaviors of different feedstock fuels under various operating conditions, pertinent to both conventional and future combustion technologies. It is well-established that particle combustion characteristics influence the design of the dimensions of pulverized fuel boilers [6].

Assessing the combustion behavior of solid fuels has been the subject of a very large number of studies in more than half a century, including Refs. [7–100] herein, with emphasis on the quantification of particle temperatures, burnout durations, as well as time delays for the particles to ignite. Such parameters affect the design of furnaces, as combustion durations affect the residence times of the combustibles therein, which then influence the selection of furnace flow-rates, which in turn affect the dimensions of furnaces. Elevated temperature profiles affect the radiative properties of the particles and gases and the convective properties of their combustion products, which in turn affect the type, dimensions and placement of the furnace/boiler heat transfer surfaces. Understandably, particle combustion characteristics are not the only factors that affect furnace design, as there are other factors as well, such as fuel particle sizing, feeding rates, fuel to air ratios, etc. Particle combustion characteristics influence the slagging and fouling propensity therein as well as the emissions of gaseous- and solid-phase pollutants therefrom. For instance, based on numerical simulation models of boiler furnace performance, Richter and Mitchell [7] concluded that knowledge of

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particle temperature (which, as they correctly stated, can easily exceed the maximum gas temperature in the flame zone by 350 K) is important for evaluation of slagging and fouling tendencies as well as for predictions of furnace heat transfer and carbon burnout. This review paper aims at contrasting the combustion characteristics of pulverized coals from various ranks and it also includes limited data on corresponding characteristics of pulverized biomasses. Both qualitative and quantitative comparisons are given on various time-dependent phenomena that take place during combustion of these fuels.

Coals are typically classified into four different ranks, lignite, sub-bituminous, bituminous, and anthracite coals. This classification is based on the history of coal formation [2]. Coal originated from peat or partially-decomposed plant materials. Increased pressure and heat from overlaying strata caused peat to dry and harden into lignite, which typically has high contents of moisture and ash and low heating value. Under higher pressure, peat formed the higher rank sub-bituminous coal. Even higher pressure resulted in the formation of bituminous or soft coal, having a higher heating value fuel. At elevated pressures, encountered in folded rock strata during creation of mountain ranges, the anthracites or hard coals were generated, possessing the highest heating values and the lowest amounts of moisture and ash than other coal types. Low rank coals contain less carbon in their structure than high rank coals. Biomass, the newest plant-based fuel, contains the least amount of carbon.

Several coals, representative of the aforesaid ranks, have been burned at the laboratory of the authors under identical high-temperature high-heating rate operating conditions and their combustion behavior has been observed at the particle level [8– 16]; past results therefrom are reviewed herein and some new results are included. Pertinent results reported in studies conducted elsewhere are also reviewed and compared, however operating conditions therein varied and thus results are not always comparable. Some of those studies were conducted in electrically-heated drop-tube furnaces (DTF), whereas others were conducted in entrained flow reactors (EFR) where streams of coal particles were injected in effluents of combustion of gaseous fuels. Drop-tube furnaces or entrained flow reactors are considered to reproduce conditions that are suitable to those in practical systems, while providing relatively simple and low-cost configurations [17–19].

Depending on the rank of coal, the geographical origin and the seam as well as the operating conditions, such as the particle size, the heating rate in the furnace, the stoichiometry and the mixing rate, the volatile matter evolution and homogeneous combustion, and the heterogeneous combustion of the solid residue may occur separately or simultaneously [20, 21]. In the early stages of combustion, a coal particle reaches sufficiently-high temperatures to release volatile matter, which surrounds the surface of the particle forming tar, soot, light hydrocarbons and hydrogen [22–27]. As devolatilizing gases diffuse/transport from the particle interior to its surface they cause swelling in bituminous coals [28, 25, 29, 8] or fragmentation in low rank coals [11,25,30]. Such phenomena provide clear examples of how the devolatilization processes of coal types differ, based on the coal rank [30, 24, 31–34]. Seeker et al. [35] and McLean et al. [36] published photographic evidence on the combustion behavior of bituminous and lignite coals at the Sandia laboratories' laminar flow reactor, whereas Timothy et al. [37] provided photographic evidence and quantitative information on the formation and characteristics of volatile flames (soot mantles) surrounding bituminous coal particles in a DTF. Sarofim, Beer and co-workers pioneered a two-color pyrometric technique that enabled them to gather further information on temperatures and burnout profiles of single lignite and bituminous coal particles burning in a DTF at various oxygen partial pressures in nitrogen [38]. Hernberg et al. [79] reported that pyrometric temperatures of coal beds agreed with temperatures from thermocouple readings. Atal and Levendis [8] obtained high-speed cinematographic images as well as three-color pyrometric temperatures and burnout times of single bituminous coal particles burning in a DTF in air, where the volatile flame and char combustion phases were resolved and assessed. This was followed by recent studies at the authors' laboratory on the qualitative and quantitative ignition and combustion behavior of single coal particles in a DTF, at oxygen partial pressures spanning 20–100% in nitrogen or carbon dioxide background gases, the later used to simulate dry oxy-combustion [10–16]. This was complemented by modeling of relevant combustion phenomena observed in the aforesaid studies [39]. In parallel investigations, Shaddix and co-workers used the Sandia laminar entrained flow reactor to conduct comprehensive studies on the combustion of coals and chars of various ranks at oxygen partial pressures spanning 12-36%, in nitrogen and carbon dioxide [40–42]. Concurrently, Zhang et al. [43,44] studied the combustion behavior of streams of a Victorian brown coal in a DTF, whereas Kim and coworkers [45] examined the combustion characteristics of sub-bituminous coals. Recently, Lee and Choi [46] recorded the volatile phase combustion characteristics of bituminous particles as a function of their size.

In the following sections, important findings of single particle investigations are contrasted and discussed. Emphasis is given to results obtained in the laboratory of the authors where operating conditions were kept identical. Therein pulverized coal particles of all ranks were burned in the same apparatus, an electrically-heated drop tube furnace (TDF) and associated diagnostic methods, under analogous gas temperature, gas flow properties (quiescent), similar particle sizes, etc. [13–15, 39, 47]. The burned coals included one anthracite (herein labeled *An*) from Asturias, Spain (code named AC), one semi-anthracite (herein labeled: *S-An*) Hullera Vasco Leonesa in León, Spain (code named HVN), three bituminous (*Bit1:* Pittsburgh #8, Pennsylvania, USA, (PSOC-1451)**,** *Bit2:* a Mexican (UM), *Bit3:* a South African (SAB)), one sub-bituminous (*S-Bit*) from River Basin, Wyodak, Wyoming, USA, (DECS-26), and two lignites (*Lig1:* Titus, Texas, USA, (PSOC-1443) and *Lig2:* Beulah, North Dakota, USA, (DECS-11)). All particles were in the size range (75–150 μm), which is relevant to pulverized fuel combustion. A biomass (sugar cane baggasse) (*Bio*) has been also added here to represent a limiting case for new plant-based fuels. Combustion of biomass particles has been studied at the authors' laboratory in the same apparatus as the coals and under similar conditions [11,13,57]. Selected results from the above studies are included herein, along with some new results. Thereafter, comparisons are made with pertinent results obtained elsewhere, most often under different, but yet relevant conditions. However, as the conditions differed in those studies the data could not be included in the plots herein.

2. Phenomenological combustion observations

2.1. Conventional combustion in air

High-speed high-resolution cinematography sequences of single particles 75–150 μm burning in still air (quiescent flow) are shown in Fig. 1. The combustion behaviors of coal particles are strikingly differentiated according to their ranks. Such combustion behaviors affect the residence times and the radiative properties of the particles in the furnace. Anthracite particles ignited heterogeneously and also burned heterogeneously in one phase. Some semi-anthracite particles ignited homogeneously and burned in two phases (a faint volatiles flame followed by char combustion), as shown in Fig. 1, and some ignited heterogeneously and also burned heterogeneously in one phase. All bituminous particles of this size range, from four different sources, ignited homogeneously and burned in two phases (volatiles flame and char combustion). Volatile flames were highly sooty and luminous, most often leading to soot contrails as the particles settled by gravity. The typical combustion behavior of a North American bituminous coal is shown in Fig. 1. Bituminous coal

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