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Measurement and numerical simulation of ultrafine particle size distribution in the early stage of high-sodium lignite combustion

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Abstract

The formation of ultrafine particulate matter in the early stage of high-sodium lignite combustion was quantitatively investigated in a downward Hencken flat-flame burner under two ambiences of 1200 K and 1500 K. Spatially resolved measurement of the ultrafine particle size distributions (PSDs) was made by using a scanning mobility particle sizer with a high sensitivity in the 4.45–156.8 nm size range. The experimental results indicate that, during the residence time of coal particles from ~20 ms to ~40 ms, the number PSDs under 1200 K exhibit bi-modal while those under 1500 K keep uni-modal. As time is evolved, the detected peak of ultrafine particles moves from 10.62 nm to 80.54 nm under 1200 K, while that from 10.76 nm to 38.46 nm under 1500 K. Then, a physico-chemical mechanism responsible for the incipient formation of ultrafine particles during high-sodium lignite combustion was developed and computed by solving a discrete-sectional population balance model. The number PSDs of ultrafine particles and the dynamic behavior of Na release measured in experiments are consistent with the simulation results. It is further divulged that the intrinsic cause of the PSD transition between different ambient temperatures is the high concentration of newly formed particles, instead of the enhanced collision frequency.

Keywords: Zhundong lignite; Ultrafine PM; Number PSDs; Population balance; Hencken burner

1. Introduction

Pulverized coal combustion (PCC) has become one of the major contributors to the serious fine particulate matter (PM) pollution in developing countries. Compared with larger particles, submicron particles, especially ultrafine $PM_{0.1}$, are generally more minatory to human health due to their high specific surface area for toxic elements enrichment and long atmospheric residence time [1]. Moreover, the PM emissions may become more severe when the coal species utilized in PCC boilers are extended from high-rank bituminous to

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low-rank lignite. It is mainly attributed to the high content of volatile minerals contained in low-rank lignite, typically alkali and alkaline earth metals (AAEM), which tend to be released in the early stage of coal combustion and make significant contributions to the subsequent formation of ultrafine PM [2,3]. In order to get an effective control of the intractable PM emission problem, an intensive focus on the fine PM formation during coal combustion is of great essence.

Previous numerical studies have developed a foundational framework on the formation mechanisms of PM with different size ranges [4–7]. Basically, the PM_1 formation mostly results from the volatilization–nucleation–coagulation mechanism [4], together with other contributions from the deformation of char particles and shedding of molten ash particles [5]. On the other hand, the $PM_{1\text{-}10}$ formation mainly originates from inherent minerals in raw coal, including the coalescence of internal minerals and the fragmentation of char and external minerals [6,7]. Nevertheless, these mechanisms were mostly deduced from the characteristics of PM samples collected at the exit of coal combustion. In order to get a straightforward description of the PM formation process, several recent studies have been focused on investigating the fine PM formed in the early stage of coal combustion, including both organic and inorganic [8–11]. One quantitative work was done by Carbone et al., who divided the PSDs of ultrafine particles into five modes and analyzed their size-segregated components [11]. However, the effect of volatile minerals, especially AAEM, enriched in low-rank lignite on ultrafine PM formation was not fully addressed yet, which motivates further quantitative studies.

In the past few decades, there has been a great effort to simulate the PM formation during coal combustion. Based on the measured mineral distributions in raw coals, two limiting cases, namely the full coalescence case and no coalescence case, were firstly reported by Loehden et al. [12]. Further, two kinds of partial coalescence models were developed, with one assuming random coalescence of the coal minerals and the other combining with an explicit char combustion model [12–14]. Additionally, the effect of char fragmentation on the PM formation was also numerically fulfilled by a series of models [15,16]. In general, these models mainly concentrated on characterizing the contribution of pre-existed minerals in coal to the PM formation, which gave out fairly good predictions on the characteristics of supermircon particles. As for submicron particles, Sarofim and coworkers once calculated their production by proposing a chemical pathway related to the release of refractory minerals during char combustion [17]. However, as for the formation of ultrafine particles, such kind of treatment did not account for the significant contribution of AAEM elements in low-rank lignite. Interestingly, in the field of flame

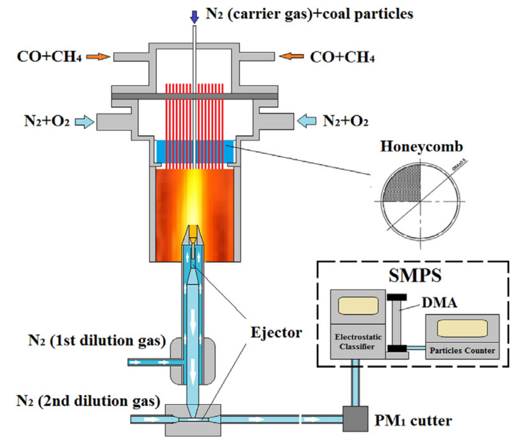

Fig. 1. Schematic diagram of the downward Hencken flat-flame burner system.

synthesis, researchers have intensively developed the discrete-sectional population balance model (PBM) to quantitatively characterize the gas-to-particle conversion process [18-21]. It is suggestible that we can extend it towards a complicated coal combustion system for predicting the ultrafine PM formation.

The object of this work is to quantitatively investigate the formation of ultrafine PM in the early stage of high-sodium lignite combustion by using a downward Hencken flat-flame burner. A two-stage isokinetic sampling probe was specially designed to collect the ultrafine PM, with number PSDs measured by the scanning mobility particle sizer (SMPS). Further, based on a proposed physico-chemical mechanism, the experimental results were simulated by solving a discrete-sectional PBM and the transition of PSDs between different ambient temperatures was intensively studied.

2. Experimental set up

2.1. Downward Hencken flat-flame burner system

The experimental system is schematically displayed in Fig. 1. It is mainly composed of two parts: the combustion part and the sampling part. The core of the combustion part is a downward Hencken burner, with a structure of hundreds of stainless steel tube embedded in a super-alloy honeycomb. The burner is capable to generate stable multi-flamelets diffusion flame, providing a hot environment for coal combustion with product gas, and reach a high heating rate of 10^5 K/s. By accurately adjusting the flow rate of fuel gas and oxidizer gas, two typical ambient temperatures, 1200 K and 1500 K, were achieved in this work. Coal particles, after dispersed by a high-frequency