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Volatile flame visualization of single pulverized fuel particles

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ABSTRACT

Experimental observation of solid particles and their volatile flames was performed to present the characteristic combustion behavior of solid fuels used in energy-production industries, i.e. coal, biomass, and petro-chemical polymers. In a hot gas stream at ~1240 K and a rapid heating rate of ~100 K/ms, time-resolved visualization of a sub-millimeter fuel particle at high magnification showed patterns of flame development of the particle, demonstrating the sub-processes of particle heat-up, devolatilization, and char combustion. The shadow images of moving particle and its surrounding volatile flame could be visualized at the same time. Repeatable experiments were able to present volatile flame patterns, which were unique in accordance with the fuel type in the corresponding combustion environment. Among the different formation patterns, a concentric and spherical volatile flame was chosen as a reference. The parameters, particle size (75–200 μm) and O_2 concentration (21.1–40.2 vol %), which affected the patterns were considered for understanding influence on them. Visible appearance was quantified by using a length scale that measured the apparent flame diameter and a set of newly-defined time scales that described its chronological variation. Using quantitative identifiers and feature descriptions, the observed flame behaviors were discussed as unique signatures for characterizing the combustion process of burning fuel particle.

1. Introduction

The solid fuel shares a large portion of energy production resources through pyrolysis, combustion, gasification, and incineration processes. Coal is the most commonly used solid fuel and fundamental research on coal combustion has served as a platform for understanding combustion phenomena of various types of solid fuel, including biomass and waste. A study on a single particle, pulverized under sub-millimeter size, has been considered to be fundamental for solid fuel combustion, whose understanding can ultimately be applied to practical engineering situations.

Coal combustion process has often been divided into consecutive steps of heat-up, devolatilization, combustion of volatiles, and char combustion. These categories have also been conceptualized from a single particle point of view, where a coal particle experiences the processes as it is introduced into a hot oxidative gas environment. This kind of description has long been proposed, and its theoretical modeling considers physical and chemical processes of a finite solid mass that combusts in an infinite gas medium. The models usually adopt simplifications, e.g., spherical symmetry for describing particle mass and transport phenomena of the combustion processes. Thus, a coal particle during volatiles combustion is idealized as a concentric volatile flame, which is analogous to the liquid fuel droplet combustion model. This analogy is reasonable in a way that an envelope flame around the single particle is evidently formed while the volatile matter emitted from pyrolysis reacts with the surrounding oxygen. This idealization, however, may not always be valid, because different types of solid fuel exhibit a wide variation in their pyrolysis and devolatilization behavior, e.g. phase, composition and yield on different chemical properties and structural forms. The oxidation behavior, such as ignition and flame formation pattern, of their volatile matter also depends on surroundings as well as its properties. In other words, the entire fate of a volatile flame, which is related to both devolatilization and volatiles combustion, relies on its fuel characteristics with thermal and fluidic combustion environment.

The ignition and combustion process have been discussed based on apparent flame behavior of solid fuel particles. Experimental investigations on volatile flames have been focused on measurement of their radiative emissions, phenomenological observation of their visible flames, and their further interpretation. Over the decades, formation of volatile flames with regard to different ranks of coal was reported [1–5], and mathematical modeling based on their physical and chemical processes was proposed [6–9]. Intense luminosity from a burning fuel particle was observable, especially during the volatile flame phase. Based on the results, Choi and Kruger [10] concluded that the radiation intensities from the volatile flame originated both from the particle surface and through the participating medium that fills the surrounding volatile flame.

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Table 1
Properties of the solid fuel particles. Polyethylene glycol, polyethylene oxide, and polyvinyl alcohol particles, which do not have practical edges for volatile flames, were excluded in the component analysis.

	Proximate analysis [wt%]				Ultimate analysis [wt%]					
	W	V.M.	F.C.	Ash	C	H	O	N	S	Cl
Bituminous F.	2.38	35.32	49.62	12.68	70.38	4.65	7.91	1.48	0.52	–
Wood	8.50	86.80	4.40	0.30	46.82	5.61	40.72	0.10	0.01	0.00
Palm kernel shell	9.75	59.57	15.93	14.75	48.42	5.73	39.05	1.04	0.014	0.012
Polyvinyl chloride	0.11	90.50	9.38	0.01	38.58	4.70	2.38	0.83	0.01	53.50

Table 2
Specification of petro-chemical polymers.

Polymer type	CAS no.	Linear formula	Average molecular weight (M_w)
Poly(vinyl) chloride	9002-86-2	$(CH_2CHCl)_n$	~80,000
Poly(vinyl) alcohol	9002-89-5	$[—CH_2CHOH—]_n$	89,000–98,000
Poly(ethylene) oxide	25322-68-3	$(—CH_2CH_2O—)_n$	~5,000,000
Poly(ethylene) glycol	25322-68-3	$H(OCH_2CH_2)_nOH$	8000

Timothy et al. [3] reported that the radiative properties of the flame mantle were considered to be important, and models were proposed based on the blackbody emission of submicron soot particles in the volatile cloud. The process of soot formation during devolatilization has been proposed, but the detailed nature of the soot has not been fully addressed. Even with these complexities, many useful observations were made with the visible emissions [1,3–5,11,12]. Typical yellow and red colors of the volatile flames were related to the blackbody radiation of the soot, and the specific color of a blue flame was also reported [2,13]. Molina and Shaddix [14] conducted the spectral measurements of the chemi-luminescence signals during volatiles ignition. From the measurements of the broadband emissions, pyrometric temperatures were determined by taking ratios of spectral intensities at the chosen wavelengths, and the data led to the volume fraction of the soot particles by using their radiative intensity, absorption coefficient, and refractive indices [3–5,11]. As the importance of co-firing combustion application of coal and biomass continues to increase more recently, some observation studies have been conducted on the combustion of biomass. They are the comparative burning behaviors of single particles of coal and biomass mixtures by Mock et al. [15], the pyrolysis and combustion characteristics of herbaceous and woody fuels by Panahi et al. [16], and the combustion process of bituminous coal and wood particles at a hot wire mesh by Riaza et al. [17].

In the present study, visual observation of volatile flames has been extended to various ranks of coal and other types of solid fuel. It provides insight on the ignition and volatiles combustion process of coal, biomass, and polymer particles in a quantitative manner. It was accomplished with the use of high-resolutions, high-speed images to investigate the in-situ combustion behavior at the single particle level from the experimental set-up established in [18]. By visualizing the volatile flame behavior, we can understand the effects of fuel type and surrounding condition on their ignition, flame formation, and extinction pattern along the time. The quantitative difference in the times required for delay and duration of the combustion processes, and flame size would give implications that verify the methodical description of single particle combustion model,

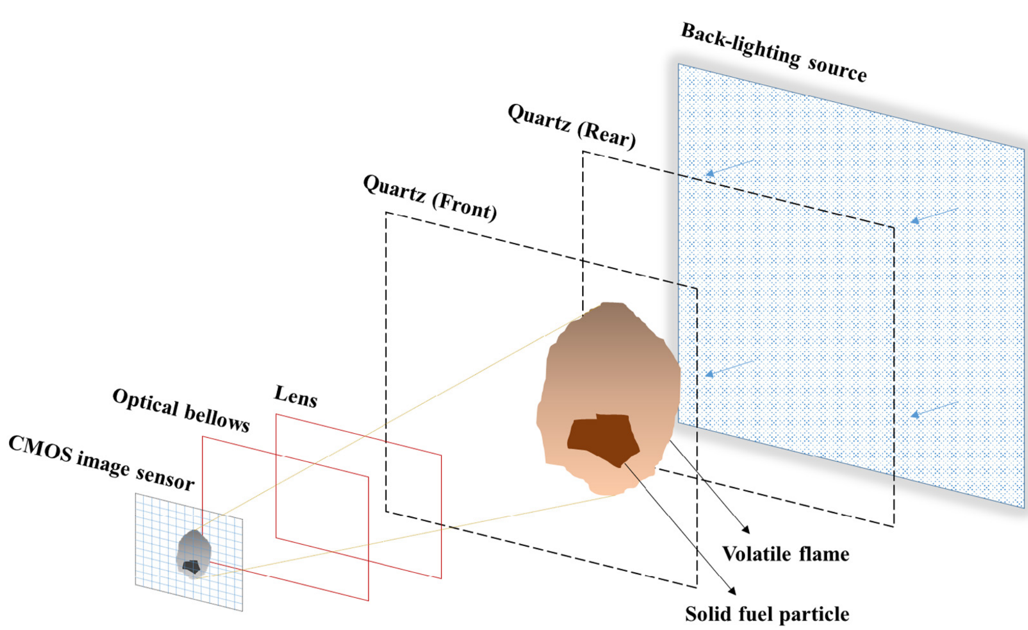

Fig. 1. Observation path through a high-speed camera with optical apparatus in high-magnification. At a CMOS (complementary metal oxide semiconductor) image sensor in the camera, moving solid particles are recorded as full-shadow images and volatile flame area is recorded as bright emission around the particles. It could be denominated as a half-shadow image in this study. The apparent characteristics of the volatile flame by radiative emission depend on sooty materials in the flame. For accurate measurements of the length scale, observational error was quantified in [18].