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Simultaneous particle size and 3D position measurements of pulverized coal flame with digital inline holography

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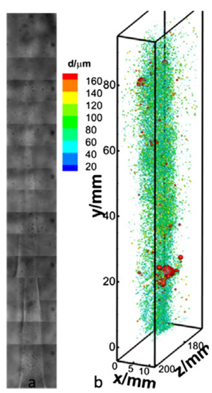
HIGHLIGHTS

- Digital inline holography is applied to measure a pulverized coal flame.
- Influences of flame on particle size and position measurement were calibrated.
- Statistical analysis on size and density distributions of sampled coal particles.

GRAPHICAL ABSTRACT



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ABSTRACT

3D measurements of burning coal particles in the flame are challenging and of great interest. Digital inline holography is applied to perform 3D measurement of coal particle size and 3D position in a laboratory-scale pulverized coal flame. Pulsed laser beam illumination is used to record the coal particle hologram with clear holographic fringes in the presence of high refractive index gradient and strong turbulence. Over 30,000 coal particles have been reconstructed and analyzed. Results show that the particle size, 3D positions and particle number density distribution can be determined simultaneously. Digital inline holography presents to be a powerful tool in the 3D measurement of burning particles in a turbulent and reacting medium.

1. Introduction

Pulverized coal combustion, in which coal is ground into fine particles with diameter of several tens of micrometers, is the most popular technology widely used for coal fired power plants. The goal of clean coal utilization to increase the energy efficiency of coal and reduce gaseous pollutants and fine particulate matter emissions, requires a deep understanding of burning behaviors of coal particles. Yet the complicated physicochemical processes of coal particle combustion, including heat and mass transfer, devolatilization, ignition and burning of volatile and char, have not been fully understood. Non-intrusive optical imaging methods were applied to observe the coal particle combustion behaviors [1,2] and measure flame properties [3–5]. The coal particle

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morphology is usually measured with microscopic imaging, which is limited to a small depth of field and thus affected by defocus particle images. The advanced laser measurement techniques used in experimental studies help to gain a deeper insight on coal particle field combustion. Laser Doppler velocimetry (LDV) is capable of measuring the velocity of coal particle inside the point probe volume, and particle image velocimetry (PIV) analyzes a pair of Mie scattering images to measure the velocity field of a planar area. LDV [6–8], PIV as well as Mie scattering imaging [9–15] have been employed to investigate the flow structure and particle distribution of pulverized coal combustion. Planar laser-induced fluorescence (PLIF) can provide species visualization via spectral imaging [8,9,11,12], such as OH. Laser induced incandescence (LII) has been developed as a tool for soot measurement [8,11]. Measurements of pulverized coal flame, which is a strongly radiating and turbulent reacting multiphase flow, have been advancing toward measuring multiple parameters simultaneously in multiple dimensions [16], especially for 3D flame measurement [17]. A combination of multiple instruments has been attempted to quantify flow fields and reaction of pulverized coal flames [8,9,11,12,14,15]. Extensions of the techniques for 3D measurement of burning coal particles, usually employ their integrations with laser scanning or tomographic imaging strategies, which dramatically increase the complicity of the measurement system. In summary, 3D measurement of burning coal particle field is of great importance in scientific aspect as well as industrial application, while few attempted due to the lack of measurement tool, and we will explore digital inline holography as a proper tool for burning particle measurement.

Digital inline holography (DIH) [18] is a real 3D imaging technique with rapid development in recent decades. Generally it involves two steps: firstly digital recording of a hologram and then numerical reconstruction of a 3D optical field from the recorded hologram. In the recording, the laser wave illuminates the object, and the light scattered by the object interferes with the reference wave, which is the undisturbed portion of the laser in Gabor inline configuration, and then the interference patterns are recorded by an array CCD/CMOS sensor as a hologram. Then in the reconstruction, the 3D optical field, from which 3D information of the interrogated object can be extracted, is numerically calculated from the back propagation of the diffraction field of the hologram illuminated by the reference wave. DIH is capable of simultaneously measuring the 3D position, size and 2D projected shape or even 3D morphology of irregular particles [19–21] in a line of sight volume spanning centimeters. Moreover, the direct integration of DIH with particle image/tracking velocimetry (PIV/PTV) strategies, namely digital holographic particle image/tracking velocimetry (DHPIV/DHPTV), has the capability of measuring both 3D translational velocity field and rotational motions of irregular particles [22–27]. With the merit of 3D measurement, DIH has been demonstrated to be a powerful tool for diagnostics of particle fields, and applied to measure sprayed droplets [28–30], moving bubbles [31–34], spherical or nonspherical solid [35–39] and even mixtures in critical phase [40] in various scenarios, including in free space [35,38,29,30], and containers with parallel windows [31,32] or curvature surfaces, such as pipes [39] and droplet inclusions [33].

Regarding to the diagnostics of burning particles with holography, reported literature can date back to 1970s with film hologram. Webster et al. [41] applied holography to measure the burning droplets with a band pass filter to eliminate the flame luminosity. Trolinger and Heap [42] investigated the burning coal particle in free flight with holography in both inline and off-axis configurations, and observed some basic phenomena of the coal particle combustion. The holography had even been used for diagnostics of the combustion of metalized fuel particle for rocket motor development [43–45]. Besides, holographic particle image velocimetry (HPIV) had been applied to the 3D flow measurement within the cylindrical optical engine [46]. The holograms in all the above holography systems were recorded with film plates. Therefore its application is limited by the complex optomechanical system for reconstructing and mechanical scanning. Compared with the film-based holography, digital holography is more convenient for the recording, storage, transfer, numerical reconstruction and automatic post processing, and therefore has also developed to be a prevalent and powerful tool in 3D measurement of burning particle field, including coal particle [48] and even metal particles [29]. BelaÏd et al. [47] had applied high speed digital inline holography to visualize the 3D trajectory of fibers drawn out of a turbulent flame. Guildenbecher et al. [29] quantitatively analyzed the shapes and 2D morphologies of reacting molten aluminum drops with a large range size from 20 μm to over 400 μm when being ejected from a burning aluminized propellants. In our past work, a DIH system had been set up and employed for the diagnostics of burning pulverized coal flame [48].

This work is to evaluate the capability of digital inline holography to simultaneously monitor particle size and 3D position in a pulverized coal flame, including feasibility demonstration as well as preliminary measurement results of a laboratory scale flame. First, the experimental setup of the digital inline holography system and the pulverized coal flame will be introduced. Then we will briefly describe the hologram processing procedures, including wavelet reconstruction method, particle locating and sizing algorithms. At last, both results and discussions based on statistics of the measured 3D position and size distribution of coal particles in the pulverized coal flame will be presented.

2. Experimental setup

Fig. 1(a) shows the sketch of the experimental setup of the digital inline holography system for coal particle flame diagnostics. A pulsed laser beam with a wavelength of 532 nm, emitted from a Nd:YAG laser (New Wave Research, Inc., Solo 120XT), and then was attenuated by an attenuator to avoid pixel saturation in the CCD sensor. The laser beam passed through a spatial filter which was comprised of an objective (40X) and a pinhole (50 μm), and then was expanded to a collimated laser beam by a spherical lens. The collimated laser beam had a diameter of about 50 mm. The duration of each laser pulse was 5 ns, which was short enough to freeze the moving coal particle. The expanded laser beam illuminated coal particles in the pulverized coal flame and propagated to the CCD. The holographic interference patterns of the objective wave diffracted by coal particles with the unscattered reference beam were recorded by a frame-transfer CCD (Lavision ImagePro), with a resolution of 1352×1248 and a pixel size of 7.4 μm. The CCD was placed about 185 mm away from the center of the pulverized coal flame. The relatively far distance of the CCD away from the flame can reduce the influence of the flame radiation on the coal particle hologram. The pulsed laser and the CCD were synchronized by a synchronizer controlled by a computer. The DIH system was operated at single pulse/single frame mode to obtain the transient hologram of burning coal particles.

A laboratory-scale pulverized coal burner was used to produce a pulverized coal flame. The burner was made of stainless steel, and mainly consisted of two coaxial tubes, as illustrated by the inset in Fig. 1(a). The inner diameter of the outer tube was 7.0 mm, and the inner tube had an inner diameter of 5.5 mm and a thickness of 0.25 mm. The annular slit burner between the inner and outer tubes had a width of 0.5 mm, and was supplied with methane. The pilot methane flame was stabilized outside of the inner tube, to ignite the coal particles. Pulverized coal particles were supplied by a screw feeder. The mass flow rate of the pulverized coal