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3D imaging of individual burning char and volatile plume in a pulverized coal flame with digital inline holography

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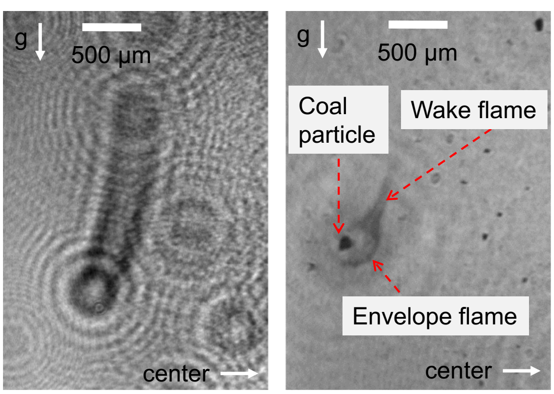
GRAPHICAL ABSTRACT

Typical hologram (left) and reconstructed image (right) of burning coal particle and its volatile flame



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ABSTRACT

The burning behaviors of an individual coal particle in the combustion of a cloud of coal particles is of great importance because it represents the realistic situation of pulverized coal particle utilization. Digital inline holography is proposed as a tool for 3D quantitative imaging of the burning coal particle and its associated volatile flame, and demonstrated by its application to a laboratory scale pulverized coal flame. The holographic fringes of burning coal particles with volatile plumes are characterized by concentric rings as well as parallel lines. Besides the conventional 3D positions and morphologies of irregular coal particles, the volatile flames are clearly reconstructed. The instantaneous behaviors of the early stage combustion of individual coal particle in a pulverized coal flame have been observed. Typical modes of the volatile flame with respect to the coal particle, including envelope volatile flame, attached wake flame, detached wake flame, side volatile flame, are observed in the experiments. The burning behaviors of one coal particle influenced by another particle in the combustion of a cloud of particles has also been evidenced. This work demonstrates that digital inline holography has the powerful capacity of simultaneously measuring reacting multiphase objects in hostile environments.

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1. Introduction

With the merit of abundant reserve and low price, coal has been, and will continue to be, one of the major sources of fossil energy in the foreseeable future. Clean utilizations of coal to power the society have been advancing with hundreds of years' laborious and ceaseless efforts, but remain unachieved with technical barriers to be overcome, such as reductions of greenhouse gas emission, pollutant emissions [1] including nitrogen and sulfur oxides, particulate matter and toxic trace elements associated with coal combustion. Among various coal utilization techniques, pulverized coal combustion by grinding coal into fine particles with size of several tens of micrometers, is the major utilization strategy in coal fired thermal power plants for electricity generation. The coal particle combustion is a complex process, and is characterized by a series of coupled thermodynamics and physicochemical kinetics, including heating up, pyrolysis and devolatilization, ignition and char burning, pollutant formation and soot aggregation. The optimized design and operation of power facilities fired by pulverized coal particle combustion through full-scale experiments or numerical simulation [2–4] on the behaviors of bulk coal combustion, require a full understanding of individual single coal particle combustion [5–16] under different conditions, which has been extensively addressed but unfortunately not been fully revealed.

In order to gain a deeper insight on coal particle combustion, several advanced optical diagnostic techniques have been applied to experimental investigations of coal particle combustion. For the morphologies of coal particles, direct microscopic imaging, which records projected images of burning coal particles, has been used as a common tool to investigate coal particle shapes, translational and rotational motions [16], ignition [6,8,11–14] and even swelling [5] or cracking [9,11,17] behaviors. The microscopic imaging with an objective to magnify the interrogated coal particles has a limited depth of field, and the trajectories of coal particles should be confined within a narrow volume in order to have their in-focus images, otherwise blurred images of coal particles at defocus positions will be observed. The lack of 3D resolution limits its wide application to the diagnostics of 3D volumetric cloud particle field. With regard to motion measurement, laser Doppler velocimetry (LDV) and particle image/tracking velocimetry (PIV/PTV) are recognized as standard tools. LDV has the capability of measuring the velocity of individual coal particle inside a point probe volume [23]. PIV is capable of measuring the velocity field in a planar area by iteratively analyzing two windowed images of a pair of Mie scattering images of dense particle field, and has been applied to measure flow fields of laboratory scale swirl pulverized coal flames [18,19] as well as pilot-scale coal-water slurry combustion furnace [20]. Concerning species measurement, spectroscopic imaging approaches are employed, such as chemiluminescence imaging and planar laser-induced fluorescence (PLIF). Chemiluminescence imaging is a passive spectral approach which uses a band-pass filter to select the band chemiluminescence of specific radicals, such as CH and C_2 [19]. PLIF records the fluorescence emitted from the excited atoms or molecules which are pumped to an excited state by a laser light illumination at a specific wavelength, and provides with a direct visualization of the species, such as OH in coal particle flame [21–23]. The above two spectroscopic methods can also be extended to gas temperature measurement. Another important parameter is coal particle temperature, and it is usually evaluated by two-color thermometry from samples of coal particle radiance in two different spectral regions. Laser induced incandescence (LII) [21,23,24] can measure soot production associated with coal particle combustion. A synergistic application of the aforementioned techniques permits simultaneous measurements of multiple parameters of coal particle combustion [19,21,23,24]. Extensions of measurement dimensions of the above 2D optical imaging techniques, i.e. for 3D measurement of burning coal particle field, usually adopt strategies of tomographic imaging from multiple views [25,26] or laser scanning from multiple layers [27], and subsequently the complexity of the measurement system increases dramatically. The irregular morphology, complicated composition and simultaneous gaseous and solid reaction make the measurement of a single coal particle combustion challenging, especially in a 3D manner.

As a real 3D imaging technique, digital inline holography (DIH) [28] has rapidly developed to be a powerful tool for 3D diagnostics of particles in recent decades. An implementation of DIH generally comprises digital recording and numerical reconstruction. In digital recording, an object is illuminated with a laser beam, and the light scattered by the object, is regarded as object wave. The object wave interferes with the undisturbed portion of the laser beam, which is called reference wave, forming interference patterns recorded by an array sensor (usually CCD/CMOS) and named a hologram. Then in numerical reconstruction, a 3D optical field is numerically revived by calculating the diffraction field of the hologram when illuminated by the reference wave in the framework of light propagation theories, and 3D information of the studied object can be extracted from the reconstructed 3D optical field with proper post processing algorithms. Compared with the conventional direct imaging, the decisive advantage of DIH is its 3D depth resolution of the probed volume with large depth of field up to centimeters. The 3D position, size and 2D projected shape or even 3D morphology of irregular particles [29–31] can be simultaneously measured with DIH. Moreover, digital holographic particle image/tracking velocimetry (DHPIV/DHPTV), enables measurements of 3D motions including both the translational velocity [32–35] and the rotation of irregular particles [36]. Successful applications of DIH to a variety of particle fields have been reported, a non-exhaustive list of examples including sprayed droplets [37–43], moving bubbles [44–48], spherical or nonspherical solids [49–55] and even mixtures of objects in multiple phases [56] under various circumstances, such as in free space [40,43,49,53], containers with parallel windows [44,45] or curvature surfaces, such as pipes [55] and droplet with inclusions [47], and in reacting medium such as burning flame and plasma. Applications of holography to combustion diagnostics of burning particles can date back to film based holography. The film based holography is inconvenient for the recording, storage, transfer, reconstruction as well as automatic post processing, and gradually replaced by digital holography. Webster et al. [57] had measured the burning droplets with a band pass filtered holography to suppress the flame radiation. Trolinger et al. [58] observed some basic phenomena of the burning coal particle in free flight with holography in both inline and off-axis configurations. Holography has even been applied for severe hostile environments with intensive combustion of metalized fuel particles in rocket motors [59–61]. Holographic particle image velocimetry (HPIV) was used for the 3D flow measurement inside a cylindrical optical engine [62]. Recently, digital holography has become a prevalent tool for the quantitative 3D diagnostics of burning fuel particles, with successful demonstrations including stick-like fibers [63], metal particles [40,64] and coal particles [65]. Belaïd et al. [63] had applied high speed digital inline holography to visualize the 3D trajectory of fibers drawn out of a turbulent flame. Guildenbecher et al. [40] and Chen et al. [64] quantitatively analyzed the shapes and 2D morphologies of reacting molten aluminum drops with a wide range of sizes 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 [65], and the 3D position and 2D shape of the irregular coal particle