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Simultaneous amplitude and phase contrast imaging of burning fuel particle and flame with digital inline holography: Model and verification

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ABSTRACT

Three-dimensional (3D) quantitative measurements of reacting multiphase micro-objects are of great interest in fuel particle combustion, which is composed of an inner fuel particle and an outer gas flame. Three models of digital inline holography of this composite fuel particle in the framework of light scattering and diffraction theories have been proposed, and then verified with reported experimental observations. Results show that the dispersed fuel particle and the gas flame distinguish in the reconstructed amplitude and phase contrast images, and reveal that the low extinction efficiency and phase shifting of the highly transparent, weakly scattering gas flame accounts for the difference.

1. Introduction

The combustion of a fuel particle usually undergoes a series of physicochemical processes. The fuel particle is heated up by external heat transfer, and then a gaseous atmosphere around the fuel particle is formed through evaporation for liquid fuel droplets or devolatilization/pyrolysis for solid fuel particles. The combustible gas fuel is ignited to burn, and the flame reinforces the process until the fuel particle is burnt out. For the solid fuel particles, e.g., pulverized coal combustion, surface oxidation occurs in the case of heterogeneous ignition. Particulate of this kind that is composed of multiple components with different properties is referred to as composite particle, and besides the burning fuel composite particle, other examples are also widely encountered in scientific researches, including cells with nucleus [1] and drops with inclusions [2]. As a special case of composite particle, the optical properties of the burning fuel particle with an associated gaseous flame [4–6] are quite different from the former two examples. The reacting flame emits a strong luminous radiation, and the light scattered by the composite burning fuel particle is also quite different. For a liquid-inclusion composite droplet, the host drop itself is a stronger scatterer than small inclusions, and the forward light scattering in the far field is dominated by the host drop. While for the composite burning fuel particle, the outer gas layer is mainly composed of gas and soot of nanoscale, and its effective refractive index is close to the surrounding medium, and much smaller than the inner fuel particle. Thus, the gas flame is a much weaker scatterer than the fuel particle, and the diffraction of the fuel particle is the major contributor of the forward scattering of the composite burning fuel particle. The detailed light interaction of the incident laser beam with a composite particle is determined by Maxwell's equations, but currently rigorous analytical solution is only available for particles of regular shapes (e.g., homogeneous or stratified spheroid [7,8]) according to generalized Lorenz–Mie theories [9,10], and light scattering by particles of irregular morphology is usually evaluated by approximated models [11].

The composite burning fuel particle is usually observed in its amplitude contrast image, such as shadowgraphy via absorption or self-luminosity image [3]. The gaseous flame is usually visualized by the spectroscopic imaging of its chemical species, such as OH

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and CH. Besides the reactive chemical radicals, there are also hot fuel vapor, gas product and particulates. This amplitude contrast method is vulnerable to image saturation due to the strong luminous radiation from the flame, and thus could not resolve the fine morphology of the flame as well as the burning fuel particle. In order to gain a higher resolution of the composite particle morphology, phase contrast imaging has been proposed, such as phase-contrast microscopy with Zernike method [12]. Therefore, imaging the composite burning fuel particle is of great challenging, and the amplitude and phase contrast images should be combined together to image its multiple phase components.

Digital inline holography (DIH) is an interesting and powerful 3D imaging technique via digital recording and subsequently numerical reconstruction. DIH has been developed to be capable of obtaining the amplitude as well as phase contrast images of an interrogated micro-object [13–19]. As regard to particle measurement with DIH, successful demonstrations of applications of DIH to various kinds of particle fields [20–23], i.e., irregular solids [24–26], deformable drops [27] and bubbles [28], have been reported. In DIH of particles in free space or other stable environments, the particle is homogeneous and thus usually treated as a pure amplitude object for a strong and absorbing scatterer or a pure phase object for a weak-scattering and transparent particle. However, for a burning fuel particle, it is undergoing intensive chemical reaction with a flame which is associated with a strong mass and heat transfer with its surrounding, and this makes the burning fuel particle neither a pure amplitude nor a pure phase object. In Guildenbecher's experiments on aluminum drop combustion [4], both the burning drop and the gaseous reacting zone as well as its surface were observed in the reconstructed amplitude contrast image. Wu et al. [5,6] employed DIH to measure the combustion of pulverized coal particle, and the reconstructed image revived the sooty volatile flame and the burning coal particle simultaneously. In these real applications, experimental results show that the holography behavior of a composite burning fuel particle presents apparent differences from that of a homogeneous particle. Consequently, models that assume the burning fuel particle as a single phase fail to explain the phenomena in composite particle holography. In fact, the composite particle of this kind in such a harsh environment has multiple phases that present different optical properties. The dispersed phase (fuel particle) is a strong scatterer with a relatively large extinction coefficient. While the continuous phase (gas flame) could be highly transparent and mainly presents phase shifting properties, and also could be absorbing when it is semi-transparent. Few particle holography models attempted to handle these composite objects [15,29]. In order to model composite particle holography, effects of different components of the composite particle on both the light scattering and phase delay of the incident laser beam should be taken into account and quantified.

This work aims to investigate the formation of holograms of composite burning gas-fuel particles as well as the characteristics of their reconstructed images. First, three models of the hologram formation in a cascade level will be derived in the framework of light scattering using Debye series and diffraction theories using matrix optics. Then, typical features of the holograms and reconstructed images will be presented and discussed.

2. Hologram model of composite burning fuel particle

Fig. 1 illustrates the schematics of DIH of a composite particle. The incident laser beam illuminates the composite particle. The composite particle has two different compositions: dispersed particle phase and continuous gas phase. The light scattered by the composite particle is the object wave **O**, and the intact part of the illumination beam is the reference wave **R**. The reference wave and object wave propagate to the CCD, and their interference pattern is recorded, named the inline hologram of the composite fuel particle, as shown in Fig. 1.

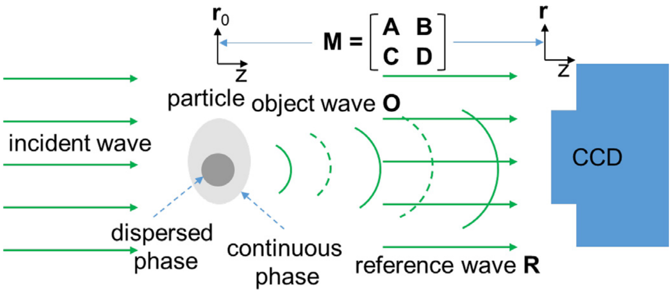

Fig. 1. Schematics of digital inline holography of a composite particle.

$$\mathbf{I}_h = [\mathbf{R} + \mathbf{O}][\bar{\mathbf{R}} + \bar{\mathbf{O}}] = \mathbf{R}\bar{\mathbf{R}} + \mathbf{O}\bar{\mathbf{O}} + \mathbf{R}\bar{\mathbf{O}} + \bar{\mathbf{R}}\mathbf{O}, \tag{1}$$

where the overbar denotes the complex conjugate.

In the classic inline particle holography, the illumination beam is a coherent Gaussian laser beam with a wavelength of λ, which is expanded and collimated with a large waist size and can be described with a complex curvature tensor $\mathbf{Q}_0^{-1}$,

$$\mathbf{U}_0(\mathbf{r}) = \exp\left(-i\frac{\pi}{\lambda}\mathbf{r}^T\mathbf{Q}_0^{-1}\mathbf{r}\right), \tag{2}$$

where $\mathbf{Q}_0^{-1} = [\begin{smallmatrix} q_x^{-1} & 0 \\ 0 & q_y^{-1} \end{smallmatrix}]$, with $q_j^{-1} = 1/\rho_j - i\lambda/(\pi\omega_j^2)$, $j \subset (x,\ y)$, with ω_j and ρ_j being the beam radius and the radius of curvature of the beam's wavefront, respectively. $\mathbf{r} = [x, y]^T$ is the position vector. The superscript T denotes the transposition. The wavefront of the laser beam on the CCD is the complex amplitude of the reference wave **R**, which usually is approximated as a plane wave because its radius of curvature is very large. Effects of the surrounding medium, e.g., the turbulent and gradient flame, on the reference beam are omitted, although they might bring slight distortion. The key to reveal the formation of inline hologram of a composite particle is to model the object wave. In the following two subsections, we will first model the object wave as well as the composite particle hologram using generalized Lorenz–Mie scattering of a multiple layered particle. Then, the object wave and hologram of an irregular composite particle are modeled using Huygens–Kirchhoff diffraction by approximating the composite fuel particle as multiple layered disks.

2.1. GLMT-based model

Generalized Lorenz–Mie theory (GLMT) is capable of describing the light scattering of a shaped beam by particles. Here we deal with a simple situation that a spherical fuel particle is concentrically located in a spherical gas flame. This is a case of droplet combustion under microgravity, where convection and buoyancy driven by gravity are non-existent and thus diffusion dominates the mass and heat transfer. Consequently, composite particle of this kind is radially symmetrical, and the gradients in temperature and species lead to a refractive index gradient. Thus, the composite particle can be regarded as a multiple layered particle, as illustrated in Fig. 2. The multiple layered particle in Fig. 2 is illuminated by an elliptical Gaussian beam. We consider a right handed Cartesian system ($Oxyz$) originates from the particle centroid and the z axis is parallel to the propagations of the incident Gaussian beam. (r, θ, φ) is the associated spherical system of the Cartesian system ($Oxyz$). The electromagnetic field (E_r, E_θ, E_φ), (H_r, H_θ, H_φ) of the light scattering at the CCD pixel which located at position (r, θ, φ) with respect to the composite particle can be described by the generalized Lorenz–