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Inverse radiation analysis for simultaneous reconstruction of temperature and volume fraction fields of soot and metal-oxide nanoparticles in a nanofluid fuel sooting flame

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ABSTRACT

An inverse radiation analysis is presented for simultaneous reconstruction of temperature and volume fraction fields of soot and metal-oxide nanoparticles in a nanofluid fuel sooting flame from the knowledge of the line-of-sight spectral radiation emission. The inverse problem is formulated as a linear optimization problem, which was successfully solved by the least-square QR decomposition method. The effects of ray number, wavelength combination and measurement error on the reconstruction accuracy were investigated. The results show that the temperature, volume fraction fields of soot and metal-oxide nanoparticles can be reconstructed accurately for the exact and noisy data.

1. Introduction

Nowadays, the urgent need for an alternative with high energy efficiency and low pollution emission to conventional hydrocarbon fuels has aroused recent research in the area of nanofluid fuels. Nanofluid fuels are uniform and stable suspensions containing available nanoscale additives in dilute concentrations (<1 vol%) [1,2]. Nanofluid heat transfer under different kinds of forces [3–12] has been deeply studied using various models [13–22] and methods [23–30], and numerous investigations have demonstrated that the nanoparticles suspended in the nanofluid can greatly enhance the heat transfer rate of the base fluid [3–9,11,13,16–22,25,27,30,31]. Moreover, a large number of studies have shown that conventional fuels with addition of nanoparticles can increase volumetric energy density [32–34], enhance burning rates [35–37], and reduce pollutant emissions [38–41]. Temperature, volume fraction fields of soot and metal-oxide nanoparticles in nanofluid fuel flame are important combustion characteristic parameters. A reliable and effective method for accurate measurement of these parameters is useful to diagnose and study nanofluid fuel flames, which promotes the practical applications of nanofluid fuel with better performance.

Measurement methods for temperature, soot volume fraction of participating media are categorized as contact and non-contact diagnostic technique. Thermocouple method is one of the most common contact methods, but soot dispersed in the flame easily deposits on the probe surface due to the thermophoresis and diffusion effects, which decreases the accuracy and sensitivity of temperature measurement. In contrast, the non-contact diagnostic techniques based on optical signals and inverse theories with efficient algorithms are more promising. Nowadays, the optical diagnostic technology for retrieving temperature, soot volume fraction and radiation properties fields of flame is developing fast and intensively, especially in terms of multiple wavelength combinations [42–44], measurement dimensions [45–54], algorithms solved for the inversion problem [47,49,51,53,55–62], instrument systems [46,63–66] and optical devices [44,52,54,67,68]. Hall and Bonczyk [42] used line-of-sight integrated measurement of boundary emission radiation at single wavelength, to reconstruct two-dimensional (2D) maps of soot temperature and concentration distributions in ethylene and *iso*-octane diffusion flames. Snelling et al. [43] applied multi-wavelength diagnostic method combined with Abel three-point inversion to determine the distributions of temperature and soot volume fraction in a symmetric diffusion flame. Ni et al. [44] used CCD cameras with liquid crystal tunable filters (LCTF) to capture multispectral flame images from which

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Nomenclature

c_1 c_2	first and second radiation constants, w m^2
$\mathbf{B}$	lower double diagonalizations matrix
C	absorption cross-section, m^2
D	particle diameter, m
fv	particle volume fraction, ppm
H_λ, $\mathbf{H}_\lambda$	monochromatic local emission source, W/(m^4 sr), and its vector
i	ith ring
I_λ, $\mathbf{I}_\lambda$	monochromatic emission radiation intensity of flame, W/(m^3 sr), and its vector
$I_{b\lambda}$	monochromatic radiation emission intensity of blackbody, W/(m^3 sr)
j	jth ray of radiation emission to spectrometer
l, $\mathbf{L}$	path of the radiation emission along the discrete direction, m, and its matrix
M	number of rings
n_λ, k_λ	monochromatic real and imaginary parts of particle complex refraction index
N	number of discrete directions of line-of-sight spectral radiation emission, i.e. ray number
N_T	number of particles per unit volume, m^{-3}
Q_λ	monochromatic absorption factor
r	outer radius of ring, mm
Rt, $\mathbf{Rt}$	volume fraction ratio of metal-oxide nanoparticles to soot and its vector
SNR_1, SNR_2	signal to noise ratio of the measurements for radiation intensity I_λ and volume fraction ratio Rt
T	temperature, K
U	total number of particles dispersed in a certain ring
$\mathbf{U}$	orthogonal matrix
V_p	total volume of particles deposited in a TEM image, m^3
$\mathbf{V}$	orthogonal matrix
Δx	interval of discrete neighboring ray, m

Greek symbols

λ	wavelength, nm
κ_λ	monochromatic spectral absorption coefficient, m^{-1}
w	wth particle
σ_1, σ_2	mean square deviations of exact radiation intensity vector $\mathbf{I}_\lambda$ and exact volume fraction ratio vector $\boldsymbol{Rt}$
ξ_1, ξ_2	random variables of standard normal distributions

Subscripts

b	*blackbody*
NPs	metal-oxide nanoparticles
exa	exact value
$meas$	measure value with error
rec	reconstruction value
rel	relative error of reconstruction value by comparison to exact value

temperature and volume fraction profiles can be retrieved, and they found that the reconstruction results using the multi-wavelength method is more accurate than the two-color method. Liu et al. [58] developed an inverse radiation analysis combined with least-square QR decomposition (LSQR) and backward Monte Carlo (BMC) methods for simultaneous estimation of temperature field and radiative properties in a 2D rectangular, absorbing, emitting and scattering gray medium from the knowledge of the exit radiative energy received by charge coupled device (CCD) cameras at boundary surfaces. Subsequently, Liu et al. [49,51] utilized multiple CCD to simultaneously reconstruct soot temperature and volume fraction distributions in three-dimensional (3D) optically thin flame. Sun et al. [52] utilized a single focused light field camera calibrated by Zhang's method [45] to measure 3D flame temperature field. Guo et al. [53] utilized double computed tomography technologies based on spatial phase-shifting method to simultaneous reconstruct 3D refractive index, temperature, and intensity distributions of flame. Xu et al. [54] proposed a novel optical sectioning tomography for the measurement of 3D flame temperature through a single camera in combination with an ionic electro wetting-based variable focus liquid lens. Niu et al. [60,61] developed hybrid LSQR-particle swarm optimization (LSQR-PSO) and LSQR-stochastic particle swarm optimization (LSQR-SPSO) algorithms to concurrent estimate 3D temperature distribution and radiative properties in participating media. A novel instrumentation system for estimating 2D and 3D distribution of temperature across a cross section of a furnace fired with pulverized coal was proposed in Refs. [51,63,64]. Huang et al. [65] designed a special stereoscopic image system by means of single-camera-based tomography measurements to obtain two or more side views for the reconstruction of soot temperature and volume fraction distributions in asymmetric diffusion flames. Brisley et al. [67] and Lu et al. [68] applied an imaging-based multicolor pyrometric system based on a novel optical splitting/filtering device for the monitoring of temperature and its distribution in a coal-fired flame.

The methods mentioned above only focused on soot involved flames, but the optical reconstruction method for metal-oxide nanoparticles contained sooting flame was insufficient. A new diagnostic for measuring metal-oxide nanoparticles volume fraction by using phase selective laser-induced breakdown spectroscopy (LIBS) during flame synthesis was developed in Refs. [69,70]. However, the LIBS method did not consider soot volume fraction distributions in flame. Niu et al. [71] and Huang et al. [72] developed a rapid computational method called generalized sourced multi-flux method (GSMFM) to simulate outgoing radiation intensities in arbitrary directions which served as input for the inverse analysis, and used hybrid algorithms to reconstructed 3D temperature distribution and radiative properties of ethylene diffusion flame filled with Al_2O_3 nanoparticles. The retrieved estimations were the average values in discrete element of the absorbing, emitting and scattering media, and the characteristic parameters for soot and Al_2O_3 nanoparticles were not respectively constructed.

In order to diagnostic nanofluid fuel flame better, the characteristic parameters fields of soot and metal-oxide nanoparticles needed to be distinguished. To our best knowledge, there is no available investigation on simultaneous reconstruction of temperature, soot volume fraction, and metal-oxide nanoparticles profiles in a nanofluid fuel sooting flame. In the present study, we develop a method for simultaneous reconstruction of these parameters in a 2D emitting medium from the knowledge of the exit line-of-sight radiation emission received by a single spectrometer at boundary surface. The inverse problem is formulated as a linear optimization problem, which was successfully solved by LSQR method.

The paper contents were organized in the following way. In Section 2, the details of the direct and inverse problems were described. In Section 3, an assumed temperature, volume fraction fields of soot and metal-oxide nanoparticles were provided for validating the method presented in Section 2, and some results and discussion for the effects of measurement errors, ray number and