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Simultaneous reconstruction of temperature and concentration profiles of soot and metal-oxide nanoparticles in asymmetric nanofluid fuel flames by inverse analysis

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ABSTRACT

An inverse analysis based on the flame emission spectrum technique is presented for the simultaneous reconstruction of two-dimensional (2D) temperature and concentration fields of soot and metal-oxide nanoparticles in the asymmetric nanofluid fuel flames by means of CCD cameras. Four CCD cameras located around the flame cross-section were used to capture the line-of-sight flame emission radiation intensities which were disintegrated to determine the radiation emission source by Least Squares QR algorithm (LSQR) algorithm. The flame cross-section was uniformly divided into several sub-squares with various grid numbers and the relationship between the grid number and the reconstruction precision was investigated in details. Considering the tradeoff between reconstruction resolution and accuracy, the optimal grid number was chosen to be 10×10. Satisfactory estimate of the three unknown fields obtained even with the signal to noise ratio of the measurement system as low as 46 dB. Numeral analyses show that the proposed reconstruction method is effective and robust for concurrent reconstructing the temperature and concentration profiles of soot and metal-oxide nanoparticles in the asymmetric nanofluid fuel flames.

1. Introduction

Nanofluid fuels are promising alternatives to the conventional hydrocarbon fuels due to its high performances in improving the energy efficiency [1–6] and decreasing the pollution emissions [7–10]. The measurements of temperature and concentration distributions of soot and the added nanoparticles are important subjects in the combustion analysis of nanofluid fuel flames.

Optical measurement approaches for soot temperature and volume fraction fields have been received extensive attention due to the minimal disturbance to the flame and the simultaneous acquisition of two-dimensional (2D) or three-dimensional (3D) reconstructed parameter profiles. Laser measurement methods [11–17] such as laser induced incandescence (LII) and laser extinction (LE) are often used in sooting flame thermometry because of the high precision and sensitivity. Greenberg and Ku [11] measured 2D soot volume fraction distributions by laser light-extinction method for normal and reduced gravity laminar acetylene jet diffusion flames. Liu et al. [12,13] determined the temperature and absorption coefficient profiles from the measured data of outgoing emission and transmission radiation intensities by conjugate gradient method and Gauss-Jordan elimination method in axisymmetric free flames. After that, they considered the influence of the turbulent fluctuation on the reconstruction of time-averaged temperature distribution [14,15] and extended a multi-wavelength inversion method in non-axisymmetric turbulent unconfined sooting flames [16].

However, it is difficult to arrange the light source and calibrate the light path in complicated conditions which largely restricts the application of the laser measurement methods. By comparison, the noncontact method based on the flame self-emission radiative energy and inverse radiation theory is much more convenient to be operated in unconfined conditions because no external light source is needed. With the developments of the algorithms to solve the inverse radiation problem and the optical devices to capture the flame emission radiative energy, the flame emission spectrum technique has been widely used to estimate 2D or 3D soot temperature, concentration and radiation properties distributions in axisymmetric and asymmetric sooting flames [18–42]. Snelling et al. [18] developed a multiwavelength flame emission technique

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Nomenclature

D	particle diameter, m
f_v	particle volume fraction, ppm
H_λ, $\mathbf{H_\lambda}$	monochromatic local emission source, W/(m^4 sr), and its vector
I_λ, $\mathbf{I_\lambda}$	monochromatic flame emission radiation intensity, W/(m^3 sr), and its vector
$I_{b,\lambda}$	monochromatic blackbody radiation emission intensity, W/(m^3 sr)
i	row-coordinate of sub-square
j	column-coordinate of sub-square
l, $\mathbf{L}$	ath of the radiation emission along the discrete direction, m, and its matrix
L_1	width of the reconstruction area
LL_1	short distance of CCD1 and CCD2 cameras away from the cross-section sides parallel to the camera
L_2	length of the reconstruction area
LL_2	short distance of CCD3 and CCD4 cameras away from the cross-section sides parallel to the camera
n_λ, k_λ	monochromatic real and imaginary parts of particle complex refraction index
N	number of detection lines received by each CCD camera, i.e. ray number
P	line number of grids in the reconstruction area
C	column number of grids in the reconstruction area
Q_λ	absorption efficiency factor
Rt	volume fraction ratio of metal-oxide nanoparticles to soot
SNR_1	signal to noise ratio of the radiation intensity measurement, dB
SNR_2	signal to noise ratio of the volume fraction ratio measurement, dB
T	temperature, K
Greek symbols	
λ	wavelength, nm
κ_λ	monochromatic spectral absorption coefficient, m^{-1}
θ	CCD camera viewing field angle
Subscripts	
b	blackbody
NPs	metal-oxide nanoparticles

for high spatial resolution determination of soot temperature and volume fraction fields in axisymmetric laminar diffusion flames. Huang et al. [19] utilized stereoscopic tomography technique for obtaining monochromatic line-of-sight flame emission projections to infer the 2D soot temperature and volume fraction profiles in asymmetric flames. Liu et al. [20,21] reconstructed 3D temperature and volume fraction distributions by LSQR algorithm from the knowledge of the flame emission radiation intensities received by CCD cameras in the symmetric and asymmetric optically thin sooting flames.

Recently, Liu et al. [43–47] considered the optical effects of multiple kinds of particles in nanofluid fuel flames and developed reconstruction methods based on the flame emission technique to reconstruct the temperature and concentration fields of soot and metal-oxide nanoparticles in axisymmetric nanofluid fuel flames. However, all the studies above were restricted to the flames with symmetric cross-section. In the practical combustion process, the nanofluid fuel flame can turn into asymmetric, for instance, the flame is in a steady and asymmetric state with a bluff body located in the burner center. Therefore, a reconstruction method for the asymmetric nanofluid fuel flame is urgently needed.

The objective of the present work was to present an inverse radiation analysis for the simultaneous reconstruction of 2D temperature and concentration profiles of soot and metal-oxide nanoparticles in asymmetric nanofluid fuel flame using CCD cameras. The flame cross-section was divided uniformly into sub-squares and the influences of the grid number and measurement error on the reconstruction accuracy were investigated. LSQR was introduced to solve the ill-posed problems of retrieving the radiation emission sources from which the three unknown profiles can be calculated by two-color method.

The paper contents were organized in the following way. The direct and inverse problems were described in Section 2. The optimal ray numbers were respectively selected in reconstruction systems with different grid numbers and the effect of grid number on the reconstruction accuracy was discussed in Section 3.1. The influence of measurement error on the reconstruction accuracy was investigated in Section 3.2. Finally, some conclusions were given in Section 4.

2. Analysis

2.1. Direct problem

The direct problem here was to calculate the flame emission radiation intensity received by four CCD cameras based on the line-of-sight method in an asymmetric nanofluid fuel flame.

Soot and metal-oxide nanoparticles with high temperatures strongly emit thermal radiation around in a continuous spectrum. The radiative information at the wavelengths within the visible range was taken into account. Therefore, the radiation emission from particles were considered but not from the gaseous compositions. Here, soot and metal-oxide nanoparticles with the size small enough ($D < 20$ nm) in the Rayleigh's theory were considered so that the scattering of these particles can be neglected. In addition, independent scattering system was considered in which the absorption coefficent in the sub-element can be represented by the algebraic sum of that of each kind of particle [43,48].

$$\begin{aligned}\kappa_\lambda(i) &= 1.5Q_{\lambda,soot}\frac{f_{v,soot}}{D_{soot}} + 1.5Q_{\lambda,NPs}\frac{f_{v,NPs}}{D_{NPs}} \\ &= 1.5\frac{\pi}{\lambda}\left(\frac{24n_{\lambda,soot}k_{\lambda,soot}}{\left(n_{\lambda,soot}{}^2 - k_{\lambda,soot}{}^2 + 2\right)^2 + 4n_{\lambda,soot}{}^2k_{\lambda,soot}{}^2}f_{v,soot}\right. \\ &\quad \left. + \frac{24n_{\lambda,NPs}k_{\lambda,NPs}}{\left(n_{\lambda,NPs}{}^2 - k_{\lambda,NPs}{}^2 + 2\right)^2 + 4n_{\lambda,NPs}{}^2k_{\lambda,NPs}{}^2}f_{v,NPs}\right) \end{aligned} \quad (1)$$

where $\kappa_\lambda(i)$ is the monochromatic absorption in the ith sub-element, Q_λ is the absorption factor calculated by Rayleigh approximation, f_v is the volume fraction, D is the particle diameter, λ is the wavelength, n_λ and k_λ are the real and imaginary parts of particle complex refraction index depended on wavelength, the subscript NPs refers to the metal-oxide nanoparticles.

The equation of radiative transfer for the participating media without the consideration of scattering effect can be written as

$$\frac{dI(s, \mathbf{s})}{ds} = -\kappa_e I(s, \mathbf{s}) + \kappa_a I_b(s) \quad (2)$$

where $I(s,\mathbf{s})$ represents the radiative intensity at position s and direction $\mathbf{s}$; $I_b(s)$ is the blackbody radiation intensity at position s obtained by the Wien's law; κ_e and κ_a are the extinction and the absorption coefficients, here $\kappa_e = \kappa_a$.

The reconstruction system to estimate temperature and concentration fields of soot and metal-oxide nanoparticles for the cross-section of the asymmetric nanofluid fuel flame was shown in Fig. 1. i and j were the row-coordinate and column-coordinate of sub-squares, respectively. Four CCD cameras with viewing field