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Estimating soot volume fraction and temperature in flames using stochastic particle swarm optimization algorithm

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ABSTRACT

A simulation investigation for simultaneous reconstruction of distributions of temperature and soot volume fraction from multi-wavelength emission in a sooting flame using the stochastic particle swarm optimizer (PSO) algorithm is presented. The self-absorption of the flame is considered. The selection of parameters of the stochastic PSO algorithm and detection wavelengths is analyzed. The effects of measurement errors and optical thickness of the flame on the accuracy of the reconstruction are investigated. It proved that the stochastic PSO algorithm is robust and can obtain accurate distributions of temperature and soot volume fraction from line-of-sight intensities in only several wavelengths, especially in the flame with large optical thickness, while other methods neglecting self-attenuation of the flame will take some errors.

1. Introduction

The understanding of soot formation mechanisms and soot radiative properties is very meaningful in flame radiation, particulate pollution emission, and combustion efficiency in combustion systems. Accurate measurement of the distributions of soot volume fraction and temperature in sooting flames has been done by many researchers, especially using non-intrusive optical diagnostic methods [1–11]. These optical methods can be divided into two categories. One category is based on laser or other additional light source. These mainly include light extinction (LE) [2,3], laser-induced incandescence (LII) [4,5], etc. The other category is based on flame emission spectra. It directly detects integral values of soot emission and then, reconstructs temperature and soot volume fraction from the flame emission spectra [6–11].

Light extinction is a path-integrated or line-of-sight technique, which provides field-integrated values of the soot volume fraction. Therefore, an inversion method is needed to reconstruct the spatial soot-volume-fraction distribution from flame-transmission maps, e.g. the Abel inversion method for axisymmetric flames as described by Snelling et al. [2] and Arana et al. [3]. Laser-induced incandescence of soot provides spatially and temporally measurements of soot distribution [4]. A calibration procedure, often based on extinction measurements or gravimetric analysis, is normally required. Recently, a two-color version of the laser-induced incandescence (2C-LII) technique has been proposed as a calibration-independent technique for absolute soot volume fraction measurements [5].

Besides that, inversion analysis has also been employed to measure the spatial distributions of soot volume fraction and temperature from multi-wavelength emission in sooting flames [6–11]. De Iuliis et al. [6] have determined soot volume fraction in an ethylene diffusion flame using an Abel inversion procedure from emission spectrum at 300–800 nm wavelength range. Snelling et al. [7] have used tomography of line-of-sight emission spectra within the 500–945 nm wavelength range for determination of distributions of temperature and soot volume fraction in an axisymmetric laminar diffusion flame using Abel three-point inversion. Daun et al. [8] proposed an inversion method based on Tikhonov regularization method for one-dimensional (1-D) inversion of soot volume fraction and showed that Tikhonov deconvolution provided more accurate results than Abel three-point deconvolution. Ayranci et al. [9] proposed an inversion scheme for optically thin axisymmetric flames for in situ characterization of soot temperature and volume fraction fields via 1-D tomographic reconstruction of line-of-sight flame emission spectra and the experiment was carried out within the 1.1–1.7 μm spectral range [10]. Huang et al. [11] attempt to reconstruct soot temperature and volume fraction distributions for the asymmetric diffusion flame using a matrix-decomposition-based least squares algorithm.

Actually, inverse radiative problem can radically come down to the entirely extremum problem of objective function constituted by the measured/desired parameters [12]. The temperature and soot volume fraction in sooting flames are strongly coupled in

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Nomenclature

B_λ	local emission source term, W/(m^4 sr)
c_1, c_2	two positive acceleration coefficient in Eqs. (6) and (8)
Δx	interval of two discrete direction, m
$E(m)$	refractive index function of soot
f_v	soot volume fraction, ppm, and its vector
$I_\lambda, \mathbf{I}_\lambda$	monochromatic radiative intensity of flame, W/(m^3 sr), and its vector
$I_{b\lambda}$	monochromatic radiative intensity of blackbody, W/(m^3 sr)
l	path of the directional radiative intensity examined
M	number of wavelength
N	number of discrete direction
n	number of optimization variables, and real part of refractive index $m = n - i \cdot k$
$p_g(t)$, $\mathbf{P}_g(t)$	best of all positions discovered by all particles at generation t and its vector
$p_i(t)$, $\mathbf{P}_i(t)$	local best position of particle i discovered at generation t or earlier and its vector
r_1, r_2	uniform random numbers in [0, 1]
$x_{ij}(t)$	position of the ith particle with jth dimension at generation t
$\mathbf{X}_i(t)$	position array of the ith particle at generation t and its vector
$v_{ij}(t)$	velocity of the ith particle with jth dimension at generation t
$\mathbf{V}_i(t)$	velocity array of the ith particle at generation t and its vector
T	temperature, K
φ	objective function
κ_λ	spectral absorption coefficient, m^{-1}
λ	wavelength, nm
τ_λ	optical length
ω	inertia factor
Subscripts	
b	black body
est	estimated value
meas	measured value

the radiative heat transfer. For the combined reconstruction of the two types of parameters, the objective function is commonly a multimodal function, and the solution of the entirely extremum problem is very difficult using traditional gradient-based methods. In previous researches, to decrease the complexity of inverse radiation problem, the flame is assumed optically thin and self-absorption is neglected. A local emission source term is reconstructed and then, the temperature and soot volume fraction is calculated from the local emission source term. Although Snelling et al. [7] proved that the influence of the attenuation error was very small for a laboratory grade flame, self-absorption should be considered in flames with higher soot loading in industrial applications.

More recently, as an alternative to gradient-based methods, some search-based intelligent algorithms, such as genetic algorithm (GA) and particle swarm optimization (PSO) algorithm, have been applied to solving the inverse radiation problems [13–19]. Compared to the traditional gradient-based methods, the intelligent optimizers have the following outstanding characteristics: the gradient information and the priori information about the objective function are not needed, and only the functional value of the objective function and primitive mathematical operators are required [12]. Li et al. [13] applied GA to determine the single scattering albedo simultaneously, the optical thickness, and the phase function from the exit radiation intensities. Kim et al. [14] proposed GA for retrieving the surface emissivity of 2-D irregular media and estimating the surface radiation of cylinder medium. Gosselin et al. [15] reviewed the utilization of genetic algorithms in heat transfer problems. As described in Ref. [20], PSO algorithm can solve most problems that GA can do, while without suffering from the difficulties of GA's, so PSO algorithm has also received much attention. Becceneri et al. [16] implemented PSO algorithm for determination of radiative properties in a 1-D plane parallel participating medium. Qi et al. [17,18] used the standard PSO, the stochastic PSO, and the multi-phase PSO to estimation of the radiative source term, optical thickness, scattering albedo, and phase function in 1-D plane-parallel participating medium. Lee et al. [19] estimated radiation properties in a two-dimensional (2-D) irregular media and compared the performance of the basic PSO, the hybrid genetic algorithm and the repulsive PSO.

In this study, PSO algorithm will be adopted to simultaneously reconstruct distributions of temperature and soot volume fraction from multi-wavelength emission intensities in an axisymmetric sooting flame. The self-absorption of the flame will be considered. Firstly, the inversion principle, including radiation model and PSO algorithm, will be described. Then, the selection of parameters of PSO algorithm and detection wavelengths is analyzed. Moreover, the effects of measurement errors and optical thickness of the flame on the accuracy of the reconstruction are investigated. Finally, some concluding remarks will be discussed.

2. Inversion principle

2.1. Radiation model

A radiation model should be established for reconstruction of distributions of temperature and soot volume fraction on a horizontal cross-section of a vertical, axisymmetric sooting flame from line-of-sight radiative emissions. The sooting flame is considered as an absorbing, emitting, axisymmetric medium with transparent boundary and there is no externally incident radiation. In the 500–1000 nm spectral range, the radiation emitted and absorbed by the suspended soot particles is considered, while the radiation emitted and absorbed by the gaseous components such as CO_2 and H_2O in the flame is neglected. As shown in Fig. 1, a spectrometer is used to scan the flame cross-section along X axis with interval Δx and the total number of line-of-sight radiative emissions received by the spectrometer is N. The monochromatic radiative intensity of soot line-of-sight emission along a chord l crossing the flame at a fixed lateral position x can be expressed as

$$I_\lambda(x) = \int_0^{l_f} \kappa_\lambda(l) I_{b\lambda}(l) \exp\left[-\int_l^{l_f} \kappa_\lambda(l')dl'\right] dl, \tag{1}$$

where l refers to the path of the directional radiation intensity examined, $I_{b\lambda}$ is the monochromatic radiative intensity of blackbody with temperature of T and wavelength of λ, κ_λ is the spectral absorption coefficient, which is directly proportional to the soot volume fraction f_v.

According to Rayleigh limit of the Mie theory, the soot volume fraction can be calculated from absorption coefficient as below [9]

$$f_v = \kappa_\lambda \lambda / (6\pi E(m)), \tag{2}$$