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Application of stochastic particle swarm optimization algorithm to determine the graded refractive index distribution in participating media

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HIGHLIGHTS

- SPSO is employed to retrieve the GRI accurately.
- Double-layer model can improve the retrieval accuracy.
- An independent model is proposed to retrieve the GRI.

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ABSTRACT

Inverse estimation of the refractive index distribution in one-dimensional participating media with graded refractive index (GRI) is investigated. The forward radiative transfer problem is solved by the Chebyshev collocation spectral method. The stochastic particle swarm optimization (SPSO) algorithm is employed to retrieve three kinds of GRI distribution, i.e. the linear, sinusoidal and quadratic GRI distribution. The retrieval accuracy of GRI distribution with different wall emissivity, optical thickness, absorption coefficients and scattering coefficients are discussed thoroughly. To improve the retrieval accuracy of quadratic GRI distribution, a double-layer model is proposed to supply more measurement information. The influence of measurement errors upon the precision of estimated results is also investigated. Considering the GRI distribution is unknown beforehand in practice, a quadratic function is employed to retrieve the linear GRI by SPSO algorithm. All the results show that the SPSO algorithm is applicable to retrieve different GRI distributions in participating media accurately even with noisy data.

1. Introduction

Radiative heat transfer (RHT) in participating media with graded refractive index (GRI) distribution has attracted significant attention in recent years due to its wide applications in various engineering fields such as combustion diagnosis, remote sensing, biological tomography, thermal protecting coating, stellar atmosphere detection, manufacturing of waveguide materials, to name a few [1–6]. Insight understanding and complete modeling of RHT in these fields depend on the accurate knowledge of the GRI distribution in participating media, which are fundamental and intrinsic parameters to determine the light transfer in these media because the GRI distribution having significant effects on radiative transfer characteristics of media. Unfortunately, in many cases of practical interest, these quantities are not known beforehand. It can't be measured directly and can only be retrieved with the help of some experimental data and corresponding inverse theory. To date, accurate determination of the GRI distribution of participating media should be considered as an unsolved problem, open to research.

To retrieve the GRI distribution, the first step is to calculate the direct radiative transfer problem for the essence of the inverse estimation which is the iterative calculation of the direct problem by updating the GRI. It is well known that the direct problem solver is very critical for an optimization approach. If the direct problem solver is not accurate enough, the optimal results cannot be obtained by such optimization approach. As most common inverse methods are multi-iterative and time consuming especially for complex geometries, developing more efficient methods is utmost necessary. With this idea in mind, the first and most essential stage in estimating GRI is to solve the direct problem efficiently. Past years have witnessed sustained efforts aimed at understanding

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Nomenclature

a	the coefficient of graded refractive index distribution $n(x)$
$\bar{a}$	the average retrieval result
b	the coefficient of graded refractive index distribution $n(x)$
c	the coefficient of graded refractive index distribution $n(x)$
c_1, c_2	the two positive acceleration coefficients in Eq. (4)
F	objective function
I	radiative intensity, $W/(m^2\ sr)$
n	the graded refractive index of participating media
$\mathbf{P}_g(t)$	the global best position discovered by all particles at generation t
$\mathbf{P}_i(t)$	the local best position of particle i discovered at generation t or earlier
R_1, R_2	the random number in the range of [0, 1]
s_j	the Chebyshev-Guass-Lobatto collation points
S	the sensitivity coefficient
T	the temperature, K
$\mathbf{X}_i(t)$	the position array of the ith particle at generation t
$\mathbf{V}_i(t)$	the velocity array of particles at generation t

Greeks symbols

χ	the derivative of refractive index with respect to the coordinate x
δ	the standard deviation
ε	the wall emissivity
Φ	the scattering phase function
γ	the measurement errors, %
κ_a	the absorption coefficient, m^{-1}
κ_s	the scattering coefficient, m^{-1}
μ	outgoing direction cosine of radiative intensity
μ'	incoming direction cosine of radiative intensity
σ	Stefan-Boltzmann constant or the standard deviation
τ	optical thickness
ψ	the dimensionless radiative intensity
ς	random variable

Subscripts

0	the left boundary
b	blackbody
est	estimated value
L	the right boundary
i	ith iteration
mea	measured value

the behavior of RHT in participating media with GRI. Numerous efforts were made to develop suitable numerical schemes for its solution. For instance, Ben Abdallah et al. [7–10] developed a curved ray tracing technique to study RHT in semitransparent media with GRI. Liu and Tan [11] adopted discrete curved ray tracing method to study transient temperature response in semitransparent media with graded index under pulse irradiation. Lemonnier et al. [12] developed a discrete coordinate method to study RHT in one-dimensional (1D) semitransparent media with GRI. Liu [13] developed a discrete curved ray tracing method to analyze RHT in 1D semitransparent media with graded index. He also derived the radiative transfer equation in three-dimensional cartesian coordinate system and developed a finite volume method (FVM) to solve RHT in multi-dimensional GRI media [14]. Xia et al. [15] adopted combined Monte Carlo (MC) method and discrete curved ray tracing method to study RHT problem in absorbing and scattering media with graded index. Recently, Li et al. [16,17] developed spectral method to solve the RHT in participating media with GRI. Due to the exponential convergence of spectral methods, a very high accuracy can be obtained even using few grids. Compared with the FVM, FEM and MCM, the spectral method costs less time in solving the same problem.

According to the discussion above, the direct radiative transfer problem within GRI media has been well established. By contrast, the inverse problem of GRI has not been well investigated and few works have focused on retrieving the GRI distribution. To date, the widely-used conventional inverse methods are gradient-based methods, including the Conjugate Gradient (CG) method, Gauss-Newton method (GN), and Levenberg-Marquardt (LM) method, etc. [18,19]. However, all these gradient-based algorithms need to solve the first or second derivative of the objective function with respect to the inversion parameters, which may be computationally expensive in terms of both memory requirements and CPU time. It is well known that the gradient-based methods converge fast but the gradient computation is sometimes complicated and the convergence depends strongly on the choice of initial guess of the unknown function [20]. Without correlative experience, it may be difficult to have a reasonable result unless a proper initial guess value is available. In a word, these methods are unable to robustly provide solutions close to the global optimal domain [21]. To circumvent this issue, the intelligent optimization algorithms based on the population exhaustive search has been proposed to solve the inverse problems in recent years, such as the Genetic Algorithm (GA), the Particle Swarm Optimization (PSO), the Ant Colony Optimization (ACO), and the Neural Network Algorithm (NNA) [22–25]. Comparing with the traditional gradient based methods which go from one approximation in the search domain to another approximation, the stochastic methods are able to search for as many solutions as possible simultaneously and thus have the potential to give unbiased estimation. A characteristic feature of these intelligent optimization methods is that they can solve the global optimal problem reliably and obtain high quality global solutions with enough computational time. They tend to perform better than the local method (gradient-based method), especially for higher problem dimensions [26]. The PSO algorithm that was first proposed by Eberhart and Kennedy in 1995 is an optimization algorithms based on swarm intelligence [27]. Its basic idea comes from the foraging behavior of birds. Group cooperation and competition among the particles produce swarm intelligence to guide the optimization search of PSO. Attractive features of PSO are simple computational process, ease of implementation and a very good convergence characteristic. As a high efficiency, simple parallel search algorithm, PSO algorithm has attracted increasing attention and widely applied in all kinds of optimization problems in recent years. Our group [23] applied the stochastic PSO (SPSO) to retrieve the absorption, scattering, extinction coefficients and radiation source term. After that, the radiation source term, optical thickness, albedo and scattering phase function are inversed by adopting multi-phase particle swarm algorithm (MPPSO) [28]. The PSO-based algorithms were also employed to solve transient radiation problems by our group [29]. Yuan et al. [30] adopted SPSO to identify the aerosol particles particle size distribution based on atmospheric radiative transfer model. Farahmanda et al. [31] utilized PSO algorithm to perform optimization study on two-dimensional radiation chamber with diffuse gray boundary. Compared to the inverse radiative problems above, the