Postprint: Research on Non-contact Measurement Algorithms for Field Parameters in Translucent Media

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Abstract

This study employs the line-of-sight method to calculate the distribution of outgoing radiation intensity at the medium boundary along a detection direction, which serves as input data for the inverse problem, accounting for absorption, emission, and scattering attenuation effects in semi-transparent media. The LSQR method is utilized to reconstruct the three-dimensional temperature distribution of the medium when the radiative property parameters are known. Reconstruction results indicate that the LSQR method can effectively reconstruct the three-dimensional temperature field of the medium under known radiative property parameters, irrespective of measurement errors. Building upon this, the LSQR-SPSO hybrid algorithm is proposed and applied to simultaneously reconstruct the three-dimensional temperature field and radiative property parameters (absorption coefficient, scattering coefficient). Computational results demonstrate that the LSQR-SPSO hybrid algorithm can effectively reconstruct the absorption coefficient, scattering coefficient, and three-dimensional temperature field of the medium simultaneously, with or without measurement errors; comparatively, the temperature field of the medium is more readily reconstructed.

Full Text

Preamble

Research on Non-Contact Measurement Algorithm for Retrieving Parameter Distributions in Semi-Transparent Media

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Abstract: For semi-transparent media considering only absorption, emission, and scattering attenuation characteristics, the outgoing radiative intensity distributions at boundary surfaces were simulated using the line-of-sight (LOS) method to serve as input for inverse analysis. The least-square QR decomposition (LSQR) algorithm was employed to estimate three-dimensional temperature distributions in semi-transparent media with known radiative properties. Retrieval results demonstrate that temperature distributions can be accurately reconstructed even with noisy data. For participating media with unknown radiative properties, a hybrid least-square QR decomposition-stochastic particle swarm optimization (LSQR-SPSO) algorithm was developed to simultaneously estimate 3-D temperature distributions and radiative properties (absorption and scattering coefficients). Retrieval results show that absorption coefficients, scattering coefficients, and 3-D temperature distributions can all be accurately reconstructed even with measurement errors. It was also found that the temperature field can be estimated more accurately than the radiative properties.

Keywords: LSQR-SPSO; Temperature field; Radiative properties; Inverse problem

0 Introduction

Temperature measurement techniques for media can be broadly classified into contact and non-contact methods. Contact measurement primarily employs various physical probes such as thermocouples, temperature-sensitive paints, and resistance temperature detectors. However, these classical contact methods not only disturb the flow field and suffer from large measurement errors, but are also unsuitable for many applications. More importantly, contact methods struggle to achieve temperature distribution measurements. Non-contact radiation imaging thermometry, which processes radiative images from media, offers advantages including high measurement precision, non-intrusive operation, and real-time continuous monitoring, while also providing three-dimensional temperature distribution information. This approach undoubtedly represents a highly promising research direction.

Nevertheless, this technology cannot directly obtain internal temperature distributions through CCD cameras or thermal imagers. It requires establishing complex inverse radiation calculation models and typically necessitates prior knowledge of the medium’ s radiative properties. The core challenge in non-contact radiation imaging thermometry lies in developing efficient, accurate, and stable reconstruction algorithms for temperature fields and property distributions, which has become a widely studied topic in recent years.

Liu and Tan et al. [1] proposed a hybrid method combining network search with conjugate gradient for simultaneously retrieving radiation source terms and wall emissivities in one-dimensional semi-transparent media. Qi and Ruan et al. [2, 3] first introduced intelligent particle swarm optimization to inverse radiation problems, discovering its advantages of being independent of initial guesses and not requiring derivative calculations of objective functions. Zhou and Zheng et al. [4] developed methods for jointly retrieving temperature and radiative properties in one-dimensional media. Lou et al. [5] proposed a decoupled method for simultaneous reconstruction of temperature distributions and radiative property parameters in one-dimensional optically thin flames or non-scattering dispersive media. Liu et al. [6] employed the least-square QR decomposition (LSQR) method combined with reverse Monte Carlo method to retrieve two-dimensional participating medium temperature fields and radiative properties. Klose et al. [7] investigated steady-state optical tomography using finite difference discrete ordinates methods and quasi-Newton methods. In summary, current research on temperature field reconstruction in participating media has primarily focused on one- and two-dimensional cases, mostly requiring known or assumed radiative properties, while simultaneous reconstruction of three-dimensional temperature distributions and multiple radiative properties remains relatively unexplored.

Temperature field reconstruction in participating media represents a typical ill-posed problem. Traditional solution methods include Tikhonov regularization, truncated singular value decomposition (TSVD), and LSQR methods. This paper addresses semi-transparent media considering absorption, emission, and scattering attenuation. With known radiative properties, the LSQR method is employed to reconstruct three-dimensional temperature distributions using radiative intensity information measured at medium boundaries. For unknown radiative properties, a stochastic particle swarm optimization (SPSO) algorithm is integrated with LSQR to form a hybrid LSQR-SPSO algorithm for simultaneous reconstruction of three-dimensional temperature fields and radiative properties (absorption and scattering coefficients).

1 Radiative Transfer Forward Problem

For semi-transparent media considering only absorption, emission, and scattering attenuation, the line-of-sight method can be used to calculate radiative intensity along any detection direction. The radiative transfer equation can be expressed as:

$$\frac{dI}{d\tau} = -I + (1-\omega)I_b + \frac{\omega}{4\pi}\int_{4\pi} I \, d\Omega$$

where I is the directional radiative intensity, τ is the optical thickness, κ_a is the absorption coefficient, κ_s is the scattering coefficient, and $\omega = \kappa_s/(\kappa_a + \kappa_s)$ is the albedo.

Consider the cylindrical semi-transparent medium model shown in Figure 1 with transparent boundary conditions and negligible environmental radiation. The expression for outgoing radiative intensity at the boundary in an arbitrary direction $\mathbf{r}$ is:

$$I = \sum_{j=1}^{n} I_{b,j} \left[1 - \exp(-\tau_j)\right]$$

where n is the number of grid cells intersected by the detection line in direction $\mathbf{r}$, τ_j is the optical thickness of the j-th grid cell, $I_{b,j}$ is the blackbody radiative intensity of the j-th grid cell, and T_j is the temperature of the j-th grid cell.

Dividing the detection plane in direction $\mathbf{r}$ into M elements yields a system of equations relating temperatures inside the medium to outgoing radiative intensities at the boundary, which can be written in matrix form:

$$\mathbf{A}\mathbf{I}_b = \mathbf{I}_n$$

where $\mathbf{A}$ is the coefficient matrix, $\mathbf{I}_b$ is the blackbody radiative intensity vector, and $\mathbf{I}_n$ is the outgoing radiative intensity vector measured by detectors.

2.1 3D Temperature Field Reconstruction Using LSQR Method

With known radiative properties, equation (3) constitutes a linear system that can be solved directly using the LSQR method to reconstruct the three-dimensional temperature field from measured radiative intensity distributions. The LSQR method, proposed by Paige and Saunders [8] in 1982, is particularly suitable for solving large, sparse linear systems. The approach involves first converting the arbitrary coefficient matrix equation into a square matrix equation, then applying the Lanczos method to obtain the least-squares solution.

2.2 Simultaneous Reconstruction of 3D Temperature Field and Radiative Properties Using LSQR-SPSO Hybrid Algorithm

When medium radiative properties are unknown, simultaneous reconstruction of temperature field and radiative properties from measured radiative intensity distributions becomes necessary. In this case, equation (3) becomes a nonlinear system that cannot be solved directly using LSQR. Therefore, this paper introduces the SPSO algorithm and combines it with LSQR for simultaneous reconstruction.

The SPSO algorithm, first proposed by Zeng et al. [9], guarantees convergence to the global optimum with probability 1 and has been widely applied to various optimization problems [10]. Compared with basic PSO, SPSO removes the previous velocity term, causing velocity to lose its memory and reducing global search capability. However, this ensures that at least one particle stops evolving at each generation due to being at the swarm' s historical best position, and utilizing these stationary particles to improve global search capability represents the fundamental concept of SPSO.

For simultaneous reconstruction of temperature field and radiative properties, radiative intensity distributions $\mathbf{I}_{n1}$ and $\mathbf{I}_{n2}$ measured by detectors in two different directions ψ_1 and ψ_2 are required as known conditions. The SPSO algorithm searches for absorption coefficients while LSQR calculates an assumed temperature field $\mathbf{T}'$ based on radiative intensity distribution $\mathbf{I}_{n1}$ in direction ψ_1. The assumed radiative intensity distribution $\mathbf{I}'_{n2}$ in direction ψ_2 is then computed from the assumed temperature field $\mathbf{T}'$ through the forward problem. An objective function is constructed by comparing this with the actual measured radiative intensity $\mathbf{I}_{n2}$ in direction ψ_2:

$$R(\kappa_a, \kappa_s) = \|\mathbf{I}_{n2} - \mathbf{I}'_{n2}\|^2$$

The SPSO algorithm searches for optimal absorption and scattering coefficients that minimize this objective function, thereby achieving simultaneous reconstruction of absorption coefficient, scattering coefficient, and three-dimensional temperature distribution.

3 Reconstruction Results and Analysis

The cylindrical geometry model shown in Figure 1 has a radius of R, grid division of $N_r \times N_z$, N_d detection lines, and axial length of 20 m. The true temperature field is assumed according to equation (5), where z is the axial coordinate and r is the radial coordinate of the cylinder.

3.1 Analysis of Temperature Field Reconstruction Results Using LSQR Method

First, assuming known radiative properties with absorption coefficient κ_a and scattering coefficient κ_s (given values), and true temperature distribution according to equation (5), the three-dimensional temperature distribution was reconstructed using LSQR based on radiative intensity measured by a detector in the direction $\theta = 90^\circ$, $\varphi = 45^\circ$. Reconstruction results under conditions of no measurement error, 1% error, and 3% error are shown in Figure 2.

As evident from Figure 2, excellent temperature field reconstruction is achieved regardless of measurement errors. The reconstruction error distributions for each grid cell under different error conditions are shown in Figure 3. Without measurement error, temperature field reconstruction errors range from 10^{-11} to 10^{-15}. As measurement error increases, reconstruction error also increases, but even with 3% measurement error, the maximum temperature field reconstruction error is only 0.96% with an average error of 0.12%. These results demonstrate that with known radiative properties, the LSQR method can effectively reconstruct three-dimensional temperature fields with good computational accuracy and stability.

3.2 Analysis of Simultaneous Reconstruction Results for Radiative Properties and Temperature Field

Assuming unknown radiative properties, the true absorption coefficient is κ_a m^{-1} (search range [0.1, 1.0] m^{-1}) and the true scattering coefficient is κ_s m^{-1} (search range [1.0, 2.0] m^{-1}). The true temperature distribution follows equation (5). Simultaneous reconstruction of absorption coefficient, scattering coefficient, and three-dimensional temperature distribution was performed using the LSQR-SPSO method based on radiative intensity distributions measured in two directions: $\theta = 90^\circ$, $\varphi = 35^\circ$ and $\theta = 60^\circ$, $\varphi = 45^\circ$. Reconstruction results for absorption and scattering coefficients under different measurement error conditions are presented in Table 1.

Regarding radiative property reconstruction, Table 1 shows that both absorption and scattering coefficients can be accurately retrieved without measurement error. With measurement errors present, reconstruction errors for both coefficients increase with error magnitude but remain within reasonable bounds. Thus, the LSQR-SPSO hybrid algorithm can successfully reconstruct medium absorption and scattering coefficients regardless of measurement errors.

For temperature field reconstruction, error distributions for each grid cell under different measurement error conditions are shown in Figure 4. Without measurement error, temperature field reconstruction errors are on the order of 10^{-5}. As measurement error increases, reconstruction error also increases, but even with 3% measurement error, the maximum temperature field reconstruction error is only 1.26% with an average error of 0.70%. These results demonstrate that the LSQR-SPSO algorithm can effectively reconstruct both radiative properties and three-dimensional temperature fields simultaneously.

Furthermore, it was observed that during simultaneous reconstruction, the temperature field is more easily retrieved with higher accuracy compared to radiative properties, which are relatively more difficult to reconstruct. This may be attributed to lower sensitivity of measurement data to radiative properties or potential multi-valued solutions for these parameters.

4 Conclusions

This paper addresses semi-transparent media considering only absorption, emission, and scattering attenuation. Using radiative intensity distributions at medium boundaries calculated by the line-of-sight method as input, the LSQR method was employed to reconstruct three-dimensional temperature distributions with known radiative properties. Building upon this, a hybrid LSQR-SPSO algorithm was proposed for simultaneous reconstruction of three-dimensional temperature fields and radiative properties.

The results demonstrate that with known radiative properties, the LSQR method can accurately reconstruct three-dimensional temperature fields regardless of measurement errors. With unknown radiative properties, the

LSQR-SPSO hybrid algorithm can successfully reconstruct absorption coefficients, scattering coefficients, and three-dimensional temperature fields simultaneously, even in the presence of measurement errors. This proves that the LSQR-SPSO hybrid algorithm possesses high computational accuracy and good stability, making it widely applicable for reconstructing radiative properties and temperature fields in semi-transparent media. Additionally, during simultaneous reconstruction, the temperature field is more readily retrieved than radiative properties.

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Note: Figure translations are in progress. See original paper for figures.