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On the treatment of non-optimal regularization parameter influence on temperature distribution reconstruction accuracy in participating medium

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ABSTRACT

The choice of the regularization parameter plays a very important role in the inverse radiation problem of temperature distribution in participating medium and in practice the regularization parameter is not easy to determine accurately, which can directly affect the reconstruction accuracy and introduce errors into reconstruction results. This paper presents the alleviation of non-optimal regularization parameter influence on the temperature distribution reconstruction accuracy in participating medium using coupled methods, i.e., two kinds of regularization method (least square QR decomposition (LSQR) method and truncated singular value decomposition (TSVD) method) coupled with genetic algorithm (GA). The radiative heat transfer was described by the backward Monte Carlo method for its efficiency. Two kinds of temperature distributions with one peak and two peaks are considered. The results show that GA can still improve the accuracy of solutions even though the optimal regularization parameters are used in the coupled methods (LSQR-GA and TSVD-GA). GA can also reduce the temperature reconstruction errors due to the non-optimal choice of the regularization parameter and improve the accuracy of the reconstruction results in the coupled methods. Moreover, the coupled methods can even reach the same or better solutions accuracy for some samples with non-optimal regularization parameter, compared with the accuracy of solutions obtained by the single LSQR method or TSVD method with the optimal regularization parameter. This study demonstrates that the coupled method can alleviate non-optimal regularization parameter influence and obtain more accurate results for the inverse radiation problem of temperature distribution in participating medium.

1. Introduction

Thermal radiation is the dominate heat transfer mode in the high temperature devices such as combustion chambers and furnaces. Temperature measurements are essential in the combustion diagnostics and optical measurement techniques are preferred nowadays for the non-intrusive advantages. The inverse analysis of radiative heat transfer can be used for the reconstruction of the temperature field or source term distribution from system exit radiation measurements. Under the assumption of known radiative properties, Li and Özişik [1,2], Siewert [3,4], Li [5], Liu et al. [6], Liu [7] and Liu et al. [8] have reconstructed the temperature profiles or source terms in plane-parallel, spherical, and cylindrical media by the inverse analysis form the data of the radiation intensities exiting the boundaries. Li [9,10] considered the estimation of the unknown source term in two-dimensional (2-D) absorbing, emitting, and scattering rectangular and cylindrical medium. Liu et al. [11] and Liu and Tan[12] presented the inverse radiation analysis of estimating three-dimensional (3-D) temperature field or source term using conjugate gradient method that minimized the error between the calculated exit radiative intensities and the experimental data. Zhou et al. [13] has reconstructed the 3-D temperature distribution using CCD cameras based on the forward Monte Carlo (FMC) method using modified Tikhonov regularization method. Liu et al. used the FMC method and LSQR method to reconstruct the 3-D temperature field in participating medium by means of CCD camera [14], also proposed a reconstruction technique for the 3-D temperature distribution with a single CCD camera based on the backward Monte Carlo (BMC) method [15], extended the reconstruction technique based on the BMC method with a single CCD to the temperature field reconstruction in the large-scale participating medium by means of multi-CCD cameras numerically [16] and experimentally [17], and carried out the simultaneous estimation of temperature field and radiative properties in 2-D participating medium [18].

However, it is a typical ill-posed inverse problem to use the exit radiation information to retrieve the inner temperature distribution of the system. The ill-posed problem can generally be solved

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Nomenclature

$\mathbf{A}$	coefficient matrix
$\mathbf{I}_{b\lambda}$	unknown blackbody intensity vector
$\mathbf{I}_{CCD}$	intensity vector received by the CCD
$I_{b\lambda n}$	blackbody intensity
$I_{w\lambda n}$	blackbody intensity of wall
$I_{\lambda m}$	intensity received by CCD
$I_{measured,j}$	simulated measured intensity
I_j	exact intensity
l	path length
$\mathbf{P}$	constant vector
$\mathbf{T}$	temperature vector
N	total volume element number
$\mathbf{U}$	orthogonal matrix
$\mathbf{V}$	orthogonal matrix
$\mathbf{B}$	lower double diagonalizations matrix
u	left singular vectors
v	right singular vectors
M	total bundle direction number

Greek symbols

σ	mean square deviation
μ	average value
ξ	random variable
$\kappa_{\lambda n}$	absorption coefficient
w_{ms}	sign of bundle termination
ε	local emissivity

Subscripts

m	bundle direction number
n	volume element number
s	bundle number

by the regularization methods such as Tikhonov regularization method, TSVD method and LSQR method. In the regularization methods, the regularization parameter plays a very important role for the solution accuracy. But the parameter-choice method such as *L*-curve method cannot work well or can be even failed on some occasions in inverse radiation problems and the alternative method should be adopted. Therefore, the optimal regularization parameter may not be easily determined accurately in the practical use.

Genetic algorithm (GA) is the optimization method based on the Darwinian evolution and has been used more and more in the field of inverse radiation problems. Gosselin et al. [19] has given the comprehensive review of the utilization of genetic algorithm in heat transfer problems. Li and Yang [20] adopted GA as the optimizer to simultaneously estimate the single scattering albedo, the optical thickness and the phase function from the knowledge of the exit radiation intensities. Kim et al. used the hybrid GA to estimate the emissivities in a 2-D irregular geometry by inverse radiation analysis [21], presented the inverse boundary analysis of surface radiation in an axisymmetric cylindrical enclosure by hybrid GA [22], and then adopted a combined method of hybrid GA and finite-difference Newton method for the inverse radiation analysis in a cylindrical geometry [23]. Verma and Balaji [24] reported the inverse conduction–radiation problem for simultaneous estimation of the optical thickness and the boundary emissivity from the knowledge of the measured temperature profile for combined conduction and radiation in a plane parallel participating medium. Das et al. [25] used the lattice Boltzmann method and the finite volume method in conjunction with the GA to simultaneously estimate three parameters, viz. the scattering albedo, the conduction–radiation parameter and the boundary emissivity by the inverse method.

Up to now very few studies in the field of inverse radiation problems of temperature distributions in participating medium have considered the non-optimal regularization parameter influence, and how to alleviate the negative effect of non-optimal regularization parameter on the temperature reconstruction accuracy in practice. The aim of present study is to investigate the performance of the coupled methods (LSQR-GA and TSVD-GA) on alleviation of non-optimal regularization parameter negative effect on the reconstruction accuracy of the temperature distribution in the participating medium with high temperature. Temperature distributions with one peak and two peaks are considered here.

2. Analysis

2.1. Inverse model description

For large radiative source (e.g., combustion furnace) and small detector (e.g., CCD camera), the FMC method can become terribly inefficiently when the radiation onto a small spot and also onto a small direction cone is desired. In this situation, the BMC method is more efficient and convenient than the FMC method.

Now consider the system as shown in Fig. 1. Four CCD cameras were mounted on the four sides of a two-dimensional rectangular enclosure, which were marked from CCD (1) to CCD (4). The system was filled with an absorbing, emitting and scattering medium. The system was divided into $N = NX \times NY$ volume elements and the temperature and emissivity of enclosure wall were assumed to be known.

At the detector location, M directions of emitted bundles were assumed with S bundles into each direction. The following linear system of equations can be obtained [15,16],

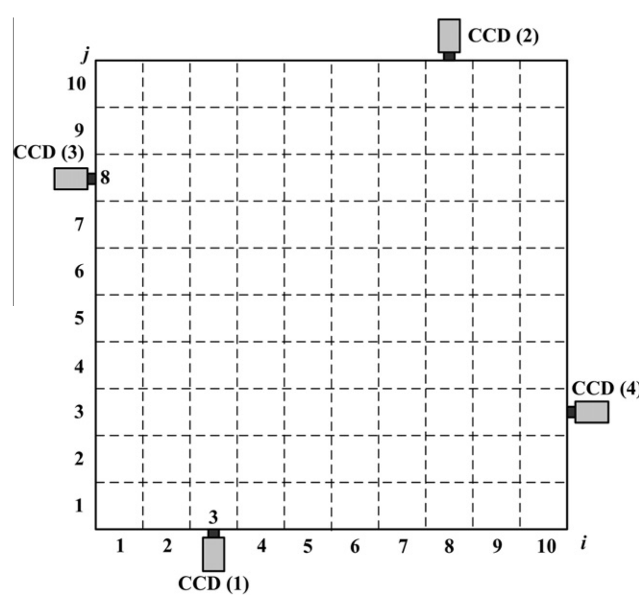

Fig. 1. Reconstruction system with four CCD cameras.