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A line-by-line hybrid unstructured finite volume/Monte Carlo method for radiation transfer in 3D non-gray medium

Hai-Feng Sun[a], Feng-Xian Sun[b,*], Xin-Lin Xia[a,*]

[a] School of Energy Science and Engineering, Harbin Institute of Technology, Harbin, China
[b] School of Power and Energy Engineering, Harbin Engineering University, Harbin, China

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ABSTRACT

A hybrid method combing the unstructured finite volume method and the Monte Carlo method and incorporating the line-by-line model has been developed to simulate the radiative transfer in highly spectral and inhomogeneous medium. In this method, the unstructured finite volume method is adopted to solve the spectral radiative transfer equation at wave numbers or spectral locations determined by the Monte Carlo method. The Monte Carlo method takes effects by firstly defining the monotonic random number relations corresponding to the spectral emitted power density of every discretized element of the concerning medium, and then by reversing the spectral location through comparison of these relations with predefined random numbers. Through this Monte Carlo method, the actual number of spectral locations on which the spectral radiative transfer equations are solved may be reduced: only the spectral locations that have higher spectral emissive powers would be more possibly selected. To increase the performance of the presented method, the total variation diminishing scheme on unstructured grids is adopted in treating the spectral radiative intensity at interface between control volumes. And, the discretized radiative transfer equation is implicitly and iteratively solved by an algebraic multi-grid solution approach to accelerate the convergence of the equation. The presented method was applied to 3D homogeneous and inhomogeneous cases for the validation and performance studies. Results show that for both cases, the presented method agree well with pure Monte Carlo benchmark solutions with acceptable number of spectral locations and computing time.

1. Introduction

For the majority of high temperature situations such as furnaces, combustion chambers, gas turbine combustor and the frontier of spacecraft in its reentry stage, radiative heat transfer is an important heat transfer mode. Methods for solving radiative heat transfer can be grouped into the stochastic or Monte Carlo method (MCM) [1–4] and the deterministic methods. The MCM uses sampling techniques to simulate the transport of photon rays. It fits for complex geometries and complex physical processes, and consumes less computer storages than the deterministic methods. Nevertheless, it requires more computation time than the deterministic methods to achieve results of negligible stochastic uncertainties. Some techniques have been developed to alleviate this problem such as the energy partition technique [1,5], the null collision meshless technique [6,7], the net exchange technique [8,9] and the stochastic spectrum determining technique [1,10]. The deterministic methods contain but are not limited to the discrete ordinate method (DOM) [2,11,12], the finite volume method (FVM) [13,14], the finite element method (FEM) [15–17] and the spectral collocation method (SCM) [18,19]. They solve the spatially and directionally discretized form of radiative transfer equation (RTE). These methods have received widespread attention as they offer a good compromise between accuracy and computational costs. In addition, they can be more easily coupled than the MCM with fluid dynamics and combustion solvers as they discretize the spatial domains in similar ways.

One distinguishing feature of the radiative transfer of high temperature systems is that there exist in the concerned medium the most significant absorbing and emitting gaseous chemical species such as H_2O, CO_2, and CO. Thus, the above numerical methods should also consider the extremely rapid spectral variations of the

Abbreviations: ADF, Absorption distribution function; AMG, Algebraic multigrid; CK, Correlated k-distribution; DOM, Discrete ordinate method; FEM, Finite element method; FSCK, Full spectrum correlated k-distribution; FV/MCM, Finite volume/Monte Carlo method; FVM, Finite volume method; LBL, Line-by-line; MCM, Monte Carlo method; RTE, Radiative transfer equation; SCM, Spectral collocation method; SLW, Spectral line based weighted sum of gray gases; TVD, Total variation diminishing; WSGG, weighted-sum-of-gray-gases.

* Corresponding authors.
E-mail addresses: fengxiansun@hrbeu.edu.cn (F.-X. Sun), xiaxl@hit.edu.cn (X.-L. Xia).

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Nomenclatures

Symbols

D	Non-uniform spectral locations density defined in Eq. (8)
D'	Uniform spectral locations density defined in Eq. (9)
D^S	Spectral location density for a control surface defined in Eq. (7)
D^V	Spectral location density for a control volume defined in Eq. (7)
I_ν	Spectral radiation intensity (W cm m^{-2}Sr^{-1})
$I_{b\nu}$	Spectral black body radiation intensity (W cm m^{-2}Sr^{-1})
N_G	Number of mesh vertexes
N_φ	Number of discrete azimuth angles
N_ν	Number of spectral locations
N_θ	Number of discrete polar angles
Q^{TOT}	Total emitted power of a medium and its boundary (W)
$\mathbf{q}$	Medium radiative flux vector (W m^{-2})
q_W	Boundary incident radiative flux (W m^{-2})
$\mathbf{r}$	Location vector (m)
R^L	Location random number relation
R^S	Spectral random number relation
s, t, u	Shape function parameters of tetrahedron element
t_{CPU}	Total computing time (s)
t_{AMG}	Time for building the spectral RTE including the AMG coarsening (s)
t_{RTE}	Time for solving spectral RTE (s)
t_{MCM}	Time for determining radiative property by the MCM (s)

Greek symbols

$\mathbf{\Omega}$, $\mathbf{\Omega}$'	Unit directional vectors
Ω, Ω'	Solid angle (Sr)
$\Delta\Omega^{GH}$	Control solid angle (Sr)
Φ_ν	Spectral scattering phase function
κ_ν	Spectral absorption coefficient (m^{-1})
$\sigma_{s\nu}$	Spectral scattering coefficient (m^{-1})
σ^M	Standard deviation of quantities.
ν	Wave number (cm^{-1})
$\overline{\Phi}_\nu^{GH,KU}$	Average spectral scattering phase function from $\Delta\Omega^{KU}$ to $\Delta\Omega^{GH}$
β_ν	Spectral extinction coefficient (m^{-1})
ε	The reflectivity of boundary
ν_{min}	The minimum wave number (cm^{-1})
ν_{max}	The maximum wave number (cm^{-1})

Subscripts

IP	Interface of vertex P with other vertexes
P	Vertex or control volume
UIP	Upwind vertex of interface IP
W	Boundary or control surface

Superscripts

G, K	Index of discrete polar angle
H,U	Index of discrete azimuth angle

Greek subscripts

ν	Spectral quantities

medium absorption coefficient. Various spectral models have been developed for determining the radiative transfer of highly spectral medium. According to their precisions to resolve the absorption spectrum in an increasing order, these models can be grouped into the gray gas model, the global models and the band models.

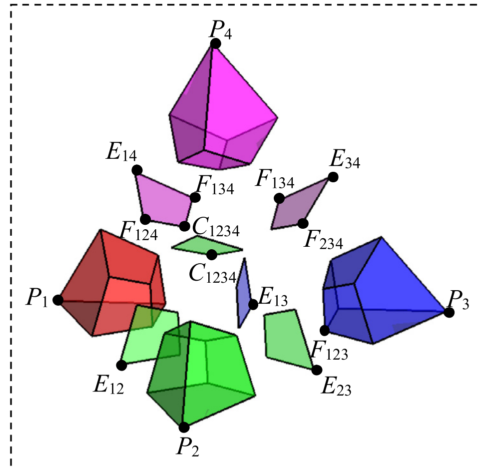

Fig. 1. A tetrahedron element and its divisions according to attached vertexes.

In the gray gas model, the absorption coefficient is treated as uniform over the spectrum. For instance, Barlow et al. [20] uses the spectral database to calculate the gray gas absorption coefficient as a blackbody emission weighted average of the spectral absorption coefficient. However, this model is of very little reliability for the computation of radiation transfer in highly spectral medium [21]. The global models contain the weighted-sum-of-gray-gases (WSGG) model [22,23], the correlated k-distribution (CK) model [24–27], the spectral line based weighted sum of gray gases (SLW) model [28,29], the absorption distribution function (ADF) model [30,31], and the full spectrum correlated k-distribution (FSCK) model [12,32,33]. And the band models include the wide band (WB) model, the narrow band (NB) model [34,35], and the line-by-line (LBL) model. In some classifications, the LBL model is seen as an independent type but here as a band model since though their spectral ranges are very small the spectrum is also represented by a number of gray bands.

The simplest and most common global model is the WSGG model. It represents the spectrum with a few gray gases that occupy certain portions of the spectrum and the transparent windows. However, it is limited to problems of non-scattering medium with gray walls. In the CK model, wave numbers of closed spectral absorption coefficients are correlated so that the spectral RTE on them can be solved simultaneously. For nearly isothermal and homogeneous medium, this model has a resolution comparable to that of the LBL model. However, for the non-isothermal and/or inhomogeneous medium, the wave numbers correlation at one position may not hold for the other. The SLW model developed by Denison and Webb [29] and the ADF model developed by Pierrot et al. [30,31] improve the WSGG model by defining similar absorption line black body distribution functions to evaluate the weight in the WSGG model. The main drawback of these models is that the scaling assumption [36] is applied to non-isothermal, inhomogeneous medium, which can be an important source of error [21]. The FSCK model developed by Modest and Zhang [33] reorders the absorption coefficient into a monotonically increasing function and defines a fractional Plank function to combine the CK model and the WSGG model. This model is equivalent to the SLW model [12], and thus also faces difficulty to be applied to medium with strong variations in the thermodynamic state [37].

All the band models resolve the spectrum by dividing it into a number of spectral bands though the bands number and parameter differ a lot. These models except the less accurate WB model cost more computer resources than the gray gas model and the global models. For example, in the statistical NB model, the bands