Journal of Quantitative Spectroscopy & Radiative Transfer 213 (2018) 17–34

Contents lists available at ScienceDirect

Journal of Quantitative Spectroscopy & Radiative Transfer

journal homepage: www.elsevier.com/locate/jqsrt

Improved spectral absorption coefficient grouping strategy of wide band k-distribution model used for calculation of infrared remote sensing signal of hot exhaust systems

Haiyang Hu[a,*], Qiang Wang[a,b]

[a] School of Energy and Power Engineering, Beihang University, Beijing 100191, China
[b] Collaborative Innovation Center for Advanced Aero-Engine, Beijing 100191, China

ARTICLE INFO

Article history:
Received 9 October 2017
Revised 28 February 2018
Accepted 10 April 2018
Available online 13 April 2018

Keywords:
Gas radiation
K-distribution
Wide-band model
Jet engine
Remote sensing thermal imaging

ABSTRACT

A new strategy for grouping spectral absorption coefficients, considering the influences of both temperature and species mole ratio inhomogeneities on correlated-k characteristics of the spectra of gas mixtures, has been deduced to match the calculation method of spectral overlap parameter used in multiscale multigroup wide band k-distribution model. By comparison with current spectral absorption coefficient grouping strategies, for which only the influence of temperature inhomogeneity on the correlated-k characteristics of spectra of single species was considered, the improvements in calculation accuracies resulting from the new grouping strategy were evaluated using a series of 0D cases in which radiance under 3–5-μm wave band emitted by hot combustion gas of hydrocarbon fuel was attenuated by atmosphere with quite different temperature and mole ratios of water vapor and carbon monoxide to carbon dioxide. Finally, evaluations are presented on the calculation of remote sensing thermal images of transonic hot jet exhausted from a chevron ejecting nozzle with solid wall cooling system.

1. Introduction

Radiation transfer in non-isothermal and inhomogeneous gas mixtures containing two or more participating species can be most accurately predicted by the line-by-line (LBL) approach [1]. However, LBL calculations require vast computer resources. Many studies have been devoted to the development of narrow-band [2], wide-band [3], and global models [2,4] to achieve acceptable accuracy at a tiny fraction of the computational cost of LBL approaches. Regarding compatibility with methods that discretize and solve the radiation transfer equation (RTE), most of these models were based on the k-distribution concept [5–8]. They addressed the radiation transfer in inhomogeneous gas using the correlated-k (CK) assumption [9], provided that the gases under various thermodynamic states have the same reordering of spectral absorption coefficients based on their values.

The CK assumption has been shown to be sufficiently accurate in cases governed by strong pressure inhomogeneities but only small temperature and species mole ratio changes [10]. Nevertheless, the CK assumption breaks down and gives poor calculation accuracy in the presence of strong temperatures or participating species mole ratio inhomogeneities [4,11]. The destruction of the CK characteristics of a gas mixture caused by the inhomogeneity of its species mole ratio is obviously due to the difference of spectra of each radiation participating species. To deal with the overlapping between absorption spectra of different species, many methods have been developed such as the multi-scale (MS) strategy based on improved convolution theory [12], partly correlated schemes [13], multiple integral methods based on uncorrelated assumptions [10], and methods based on joint distribution functions [14]. The calculation accuracies as well as the computational costs of these methods increase in sequence. The destruction of the CK characteristics caused by gas temperature inhomogeneity is because of “hot absorption lines” [15]. To overcome this problem, fictitious-gas (FG) [16] and mapping transformation [17] methods have been developed based on grouping absorption lines and spectral absorption coefficients, respectively, by their temperature dependence. The latter is also the basis of multispectral strategy [18] and various multi-group (MG) strategies [15,19]. It should be noted that the computational cost of solving RTEs also increases as the number of fictitious gases or absorption line groups increases.

For the radiance emitted by hot jet exhausted from nozzle of aircraft and attenuated by atmosphere during its long-path propagating, unfortunately, both mechanisms of destruction of CK characteristics exist simultaneously. Because the temperature of the jet

---

[*] Corresponding author.
E-mail address: 09451@buaa.edu.cn (H. Hu).

https://doi.org/10.1016/j.jqsrt.2018.04.014
0022-4073/

Nomenclature

$\bar{\mathbf{a}}$	weighting factor of radiation emission
atm	standard atmospheric pressure
G	cumulative convolution function
g	cumulative k-distribution function
H	Heaviside step function
I	radiance W/(m^2·Sr)
$\bar{\bar{j}}$	series number of spectral absorption coefficient
k	absorption coefficient cm^{-1}
L	path length of radiation transfer cm
M	total group number for one species
$\vec{n}_w$	unit vectors normal to the wall
$\mathrm{N_g}$	total number of points of Gauss quadrature
N_{nb}	total number of narrow band
P	gas pressure atm
S	similarity factor between two vectors
s	the location along the radiation transfer way
T	gas temperature K
$\mathbf{U}$	scaling vector
u	scaling coefficient
$\breve{u}$	correlation function
w	weighting value of Gauss–Legendre quadrature
x	species mole fraction
y	species mass fraction

Greek symbols

δ_η	wavenumber width of subintervals used for grouping spectral absorption coefficients cm^{-1}
$\Delta\eta$	wavenumber width of narrow band cm^{-1}
$\boldsymbol{\varepsilon}$	solid wall emissivity
ε	group tag
η	wave number cm^{-1}
λ	overlap parameter cm^{-1}
σ	Stefan–Boltzmann constant 5.67 × 10−8 W/(m^2 K^4)
$\underline{\phi}$	vector of thermodynamic state parameters
Ω	solid angle Sr

Subscripts

a	ambient air
b	black body
c	cold layer
h	hot layer
$\underline{i}, \underline{j}, \underline{\ }1, 2$	serial number of thermodynamic state
$\bar{\mathrm{i}},\bar{\mathrm{j}},\bar{\mathrm{k}}$	serial number of point of Gauss quadrature
m	group serial number
n	species serial number
w	wall
0	reference state
*	predicted or optimal value

is much higher than that of atmosphere, and the mole ratios of water vapor to carbon dioxide in the combustion gas of jet and the atmosphere are quite different. (The former depends on the composition of aviation kerosene, and is close to 1:1, when the mole ratio for the latter varies from below 1:100 to above 100:1 under different climates and altitudes.) But there is so far no method dealing with the influences of both temperature and species mole ratio inhomogeneities on the CK characteristics of a gas mixture. Because the combination of the two kinds of methods mentioned above to deal with both influences is usually accompanied by exponential increasing of computational cost as the number of participating species increases (e.g., the combination of joint distribution function and fictitious gas [14]). Although the number of solved RTE in the MSMG full-spectrum k-distribution (MSMGFSK) model, which was established by Pal and Modest [20,21] exploiting both MG and MS strategies, is proportional to the number of participating species in the gas mixture, it only allows the mole ratio of participating species to vary within a narrow range.

In this paper, first, current MG strategies based on scale approximation or CK assumption to deal with the influence of temperature inhomogeneities on the CK-characteristics of spectra of single species were outlined (Section 2). Calculation results of a few 0D cases (Section 4) showed that the errors of wide band model combined with original MSMG strategy were still too large for calculation of infrared remote sensing signal of hot jet, because the species mole ratio inhomogeneity encountered in infrared remote sensing signal calculation is much stronger than the MS strategy can handle. To overcome this problem, a MG strategy based on a new optimization criterion of dividing spectral absorption coefficients was established considering the influences of both temperature and species mole ratio inhomogeneities on the CK characteristics of spectra without further increasing computational cost (Section 3). The calculation accuracies of MSMG wide-band k-distribution (MSMGWB) model resulting from the new grouping strategy were validated in 0D cases (Section 4) and a complex 3D case (Section 5).

2. Spectral absorption coefficient grouping strategy for single species

2.1. Wide band k-distribution model

The RTE for medium containing single participating species, not considering scattering, can be written as [22]

$$\begin{cases} \frac{dI_\eta}{ds} = k_\eta(\underline{\phi})I_{b\eta} - k_\eta(\underline{\phi})I_\eta \\ I_{3-5\,\mu\mathrm{m}} = \int_{2000\,\mathrm{cm}^{-1}}^{3350\,\mathrm{cm}^{-1}} I_\eta d\eta \end{cases}, \tag{1}$$

where η is the wave number, k_η the spectral absorption coefficient, $\underline{\phi} = (T, P, x)$ the vector containing all the thermodynamic state parameters affecting k_η (temperature T, pressure P, and species mole fraction x), I_η the spectral radiance, $I_{b\eta}$ the spectral radiance of a blackbody (obeying Planck's law of blackbody radiation, and $\int_0^\infty I_{b\eta}(T)d\eta = \frac{\sigma T^4}{\pi}$), and s the location along the radiation transfer path. In this paper, the integral bounds for k_η are set from 2000 cm^{-1} to 3350 cm^{-1}, corresponding to the atmospheric infrared window of the 3–5-µm wave band.

Based on the k-distribution concept and CK assumption, Eq. (1) can be modified approximately by reordering I_η based on the value of k_η in the range $2000\,\mathrm{cm}^{-1} < \eta < 3350\,\mathrm{cm}^{-1}$ [23] to give

$$\begin{cases} \frac{dI_{\bar{g},\bar{\mathrm{j}}}}{ds} = k(T_0, \underline{\phi}, \bar{g}_{\bar{\mathrm{j}}})\Big(\bar{\mathbf{a}}_{\bar{\mathrm{j}}}(T, \underline{\phi})I_b(T) - I_{\bar{g},\bar{\mathrm{j}}}\Big) \\ g(T_0, \underline{\phi}, k) = \frac{1}{I_b(T_0)} \int_{2000\,\mathrm{cm}^{-1}}^{3350\,\mathrm{cm}^{-1}} I_{b\eta}(T_0)H\Big(k - k_\eta(\underline{\phi})\Big)d\eta \\ 0 = \tilde{g}_0 < \bar{g}_1 < \tilde{g}_1 < \bar{g}_2 < \cdots < \tilde{g}_{\bar{\mathrm{j}}-1} < \bar{g}_{\bar{\mathrm{j}}} < \tilde{g}_{\bar{\mathrm{j}}} \\ < \cdots < \tilde{g}_{\mathrm{N_g}-1} < \bar{g}_{\mathrm{N_g}} < \tilde{g}_{\mathrm{N_g}} = 1 \end{cases}, \tag{2}$$

where $T_0 = 1000\,\mathrm{K}$ is the reference temperature used in all the wide band k-distribution models of this work, g the cumulative k-distribution function (a smooth and monotonic increasing function of k, which ensures the $k(T_0, \underline{\phi}, g)$ is close to a constant within the range $\tilde{g}_{\bar{\mathrm{j}}-1} < g < \tilde{g}_{\bar{\mathrm{j}}}$ when $\mathrm{N_g}$, the total number of $\bar{g}_{\bar{\mathrm{j}}}$, is large enough), H the Heaviside step function, $I_b(T) = \int_{2000\,\mathrm{cm}^{-1}}^{3350\,\mathrm{cm}^{-1}} I_{b\eta}(T)d\eta$, and

$$\int_{2000\,\mathrm{cm}^{-1}}^{3350\,\mathrm{cm}^{-1}} I_\eta d\eta = \sum_{\bar{\mathrm{j}}=1}^{\mathrm{N_g}} I_{\bar{g},\bar{\mathrm{j}}}. \tag{3}$$