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A new model to simulate infrared radiation from an aircraft exhaust system

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Abstract A multi-scale narrow band correlated-*k* distribution (MSNBCK) model is developed to simulate infrared radiation (IR) from an exhaust system of a typical aircraft engine. In this model, an approximate approach instead of statistically uncorrelated assumption is used to treat overlapping bands in gas mixture. It significantly reduces the requirement for computing power through converting the exponential increase of computing power consumption with the increase of participating gas species to linear increase. Besides, MSNBCK model has a great advantage compared with conventional methods which can estimate each species' contribution to the total gas mixture radiation intensity. Line by line (LBL) results, experimental data and other results in the references are used to evaluate this new model, which demonstrates its advantage in terms of accuracy and computing efficiency. By coupling this model and finite volume method (FVM) into radiative transfer equation (RTE), a comparative study is conducted to simulate IR signature from the exhaust system. The results indicate that wall's IR emission should be considered in both 3–5 μm and 8–14 μm bands while gases' IR emission plays an important role only in 3–5 μm band. For plume IR radiation, carbon dioxide's emission is much more significant than that of water vapor in both 3–5 μm and 8–14 μm bands. Especially in 3–5 μm band, the water vapor's IR signal can even be neglected compared with that of carbon dioxide.

1. Introduction

Infrared stealth is one of important abilities for aircraft to prevail in modern air battle. IR emission from the exhaust system takes a great proportion in the total IR emission of an aircraft. Therefore, accurate prediction of IR signature from an exhaust system is of great significance for IR detection and aircraft propulsion system design.

IR emission from a specific exhaust system can be attributed to two parts: hot plume IR emission and high temperature engine parts IR emission, such as that of nozzle, and turbine

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blades. Compared with high temperature engine parts, radiation from the hot plume is much more complicated, since carbon dioxide and water vapor's IR emission plays a major role, which shows non-gray characteristics. With respect to non-gray gas radiative calculation, LBL method is conducted using detailed information of every needed spectral line from a high resolution spectroscopic database; therefore it is recognized as the most accurate method.[1] However, the disadvantage of this method is also very obvious, and it requires huge amount of computing power which makes it impractical to be applied to the real world. For this reason, different models have been developed to provide relatively accurate yet efficient calculations. From the functional standpoint, all these models can be divided into two kinds: one is for calculating thermal radiation such as Weighted-Sum-of-Gray-Gases (WSGG) model,[2] Spectral Line Based Weighted Sum of Gray Gases (SLW) model,[3–6] absorption distribution function (ADF) model[7] and full-spectrum k-distribution (FSK) model[8,9] and the other is for IR signal calculation such as statistical narrow band (SNB) model[10,11] and narrow band k-distribution (NBK) model.[12] The output parameter of SNB model is transmissivity, which is suitable for ray tracing RTE solver, but it is difficult to couple with differential methods such as finite volume method and discrete coordinate method. Besides, the SNB model is also incompatible with scattering from particles or soot in the plume even though different strategies have been tried to solve this issue.[13,14] In comparison, NBK model provides absorption coefficient as model output parameter which can be coupled with arbitrary RTE solution method and deal with scattering simultaneously. The principle of NBK model is that provided the medium is homogeneous and for a narrow band which is sufficiently narrow to assume a constant Planck function, the absorption coefficient can be reordered into a smooth and monotonically increasing function so that integration over the narrow band can be replaced by an integral scheme with several points. Compared with spectral evaluations for LBL, NBK model provides an efficient way to reduce the computational costs, but it is limited to calculate single homogeneous medium. Two methods have been used to deal with non-homogeneous gas, i.e. correlated-k (CK) method and scaling approximation, and the CK method assumes that the maximum absorption coefficients across the spectrum under investigation always occur at the same wavenumber, regardless of the temperature, pressure and mole fraction,[15] and are suitable for all intermediate values. The scaling approximation is inherently similar to CK method but more precise in mathematical terms. Because of less restrictiveness and acceptable accuracy, the CK method is widely used in both full spectrum and narrow band, forming FSCK model and NBCK or SNBCK model.[16,17] For all band models, treatment of overlapping bands in gas mixture is always somewhat problematic. One conventional approach is statistically uncorrelated assumption, i.e. transmissivity of a gas mixture can be obtained by multiplying transmissivity of each species. This turned to be true for narrow band but the computational costs become expensive by a factor of N^M where N is the number of integral points in solving RTE and M the number of participating gases. Depending on different assumptions, some approximate mixing models such as convolution, multiplication, superposition and hybrid approaches have also been proposed by Solovjov and Webb to deal with gas mixture's radiation in full spectrum.[18] Besides, Modest and Riazzi calculated the mixture's cumulative k-distribution function based on the multiplication of transmissivities and property of Laplace transformation.[19] Instead of treating the mixture as a single gas, it is noted that a multi-scale approach is applied in full spectrum to calculate radiation emitted by a certain gas but absorbed by all the gases. This is an approximate way but which finally achieved both reasonable accuracy and computational efficiency.[20] Above all, it increases computational costs by a factor of $M{\bullet}N$, but to date, the multi-scale concept is mainly used in full spectrum with several different models having been derived.[21–23]

In this paper, we present a narrow band model based on the CK method and multi-scale method, and to the best of the author's knowledge, such a combination (MSNBCK) has not been carried out in the past. Experimental and LBL results will serve as a benchmark to validate the accuracy of k-distribution method. When dealing with overlapping bands in gas mixture, the MSNBCK model is evaluated by comparison with exact LBL results and SNB model combined with statistical uncorrelated assumption for both isothermal and non-isothermal cases. Using the Finite Volume Method (FVM) to solve RTE and MSNBCK model and describe the property of non-gray gas mixture, simulation of the infrared signature from a realistic three-dimensional aircraft engine is conducted. Absorption coefficients of participating species are calculated from the spectroscopic database HITEMP 2010 in advance and all the IR calculation process in this paper is accomplished using C program.

2. Numerical modeling and validation

The radiative transfer equation for an absorbing, emitting and scattering medium is written as[1]

$$\frac{\mathrm{d}I_\eta}{\mathrm{d}\boldsymbol{s}} = k_\eta(I_{b\eta} - I_\eta) - \sigma_{s\eta} I_\eta + \frac{\sigma_{s\eta}}{4\pi}\int_{4\pi} I_\eta(\boldsymbol{s}')\Phi_\eta(\boldsymbol{s},\boldsymbol{s}')\mathrm{d}\Omega' \tag{1}$$

where subscript η is wavenumber, I_η spectral intensity varying along a path $\boldsymbol{s}$, $I_{b\eta}$ Planck function, k_η spectral absorption coefficient, $\sigma_{s\eta}$ scattering coefficient, $\Phi_\eta(\boldsymbol{s},\boldsymbol{s}')$ scattering phase function, and Ω' the solid angle. In the case of a gray surface which emits and reflects diffusely, boundary conditions subject to Eq. (1) can be expressed as

$$I_\eta = \varepsilon I_{b\eta w} + \frac{1-\varepsilon}{\pi}\int_{\boldsymbol{n}\cdot\boldsymbol{s}<0} I_\eta|\boldsymbol{n}\cdot\boldsymbol{s}|\mathrm{d}\Omega \tag{2}$$

in which ε is the wall's emissivity, $I_{b\eta w}$ radiative intensity of the black wall and $\boldsymbol{n}$ the corresponding surface normal vector.

2.1. k-distribution and spectral reordering

In a narrow spectral interval (generally 4–50 cm^{-1}), the Planck function $I_{b\eta}$, scattering coefficient $\sigma_{s\eta}$ and scattering phase function $\Phi_\eta(\boldsymbol{s},\boldsymbol{s}')$ can be treated as constants,[8] and the spectral intensity would obtain the same value repeatedly since the absorption coefficient attains the same value (Fig. 1) (1 atm = 101,325 Pa). Therefore, the key point of k-distribution method is to reorder the absorption coefficient into a smooth and monotonically increasing function so that RTE solution with the same absorption coefficient is carried out only once.