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A numerical simulation method for aircraft infrared imaging

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HIGHLIGHTS

- The NBK model is validated and used to predict radiative properties of non-gray gases.
- A FVBRT method is validated by comparing with the RMC method and experimental data.
- IR images with good accuracy and better rendering effects.
- Feasibility to predict IR signature of an aircraft with internal and external flow.

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ABSTRACT

Numerical simulation of infrared (IR) emission from aircraft is of great significance for military and civilian applications. In this paper, the narrow band k-distribution (NBK) model is used to calculate radiative properties of non-gray gases in the hot exhaust plume. With model parameters derived from the high resolution spectral database HITEMP 2010, the NBK model is validated by comparisons with exact line by line (LBL) results and experimental data. Based on the NBK model, a new finite volume and back ray tracing (FVBRT) method is proposed to solve the radiative transfer equations and produce IR imaging. Calculated results by the FVBRT method are compared with experimental data and available results in open references, which shows the FVBRT method can maintain good accuracy while producing IR images with better rendering effects. Finally, the NBK model and FVBRT method are integrated to calculate IR signature of an aircraft. The IR images and spatial distributions of radiative intensity are compared and analyzed in both 3–5 μm band and 8–12 μm band to provide references for engineering applications.

1. Introduction

With the development of infrared (IR) detection technology, the study on IR imaging has attracted more and more attention. Compared with experimental methods, the numerical simulation of IR imaging can be conducted with more flexibility and lower costs, and presents a good application prospect for remote detection and aircraft design.

IR signature of the aircraft or a specific exhaust system has been studied by a number of researchers in the world [1–6]. In general, IR emission from the aircraft itself can be attributed to three parts: aircraft skin IR emission, hot plume IR emission and high-temperature engine parts (such as nozzle inner wall and turbine blades) IR emission. Emission from solid walls can be calculated by the classical radiative theory, whereas radiative transfer in plume becomes somewhat complicated since the non-gray gas components (CO_2 and H_2O) show discontinuous spectral characteristics. The line by line (LBL) method, relying on detailed information of every spectral line in a high resolution database, is treated as the most accurate method to perform gas radiative calculations [7]. Because of the irregular changes of absorption coefficients, the LBL method must be conducted over many wavenumbers and thus requires intensive computational power (both CPU time and computer memory) [8]. It has been known that the LBL method is too time consuming to be applied to engineering applications [9]. Actually, the limitation of LBL method has prompted the development of different spectral models which can achieve a balance between the accuracy and computational efficiency. According to the application areas, these spectral models can be approximately put into two groups: one is used to calculate thermal radiation such as Weighted-Sum-of Gray-Gases (WSGG) model [10], Spectral Line Based Weighted Sum of Gray Gases (SLW) model [11], absorption distribution function (ADF) model [12] and full-spectrum k-distribution (FSK) model [13], all these models attempt to integrate over the global spectrum before solving radiative transfer equations; the other group,

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represented by statistically narrow band (SNB) model [14–16] and narrow band k-distribution (NBK) model [17], is mainly used for IR signal calculation whose integration interval is limited to a part of the global spectrum. It is worth noting that the spectral models in the first group can't provide spectral information that are required for IR signal calculation. But conversely, either SNB model or NBK model can be applied to calculate thermal radiation by splitting the full spectrum into a certain number of small intervals. Some mature IR calculation software, such as SIGGE developed by Swedish Defense Research Agency [18] and NIRATAM developed by NATO [19,20], has adopted the SNB model to estimate the plume IR emission. The SNB model formulates radiative properties in terms of gas column transmissivity, which implies the radiative transfer equations are generally solved by the ray tracing methods. The NBK model, in another way, provides a reordered gas absorption coefficient and radiative transfer equations can be solved by both ray tracing methods and differential methods. From the view of IR detection, only irradiation onto the detector surface is really concerned and this means the ray tracing methods are more efficient than the differential methods which calculate the intensity field everywhere. As a typical ray tracing method, the Reverse Monte Carlo (RMC) method has been applied in the software CRIRA and other related researches [21–24]. The main idea of RMC method is to send a large number of rays in the detector's field of view and then follow the progress of each ray until it is absorbed or leaves the target region. Whether the ray is absorbed or leaves away depends on the optical properties and random numbers occurring along the transfer path. Contribution of each ray is then marked with radiant energy at the ray's endpoint. This method works well with absorbing, emitting and scattering medium as well as reflective and emissive walls because all the relevant optical properties can be described by corresponding statistical criterions. In essence, the physical quantity calculated by RMC method is a statistically meaningful result, but the information carried by every detailed ray may not objectively reflect the physical fact. Thus the IR image obtained by RMC method may also misunderstand the true details even though a statistically average value in the detector's total field of view is acceptable.

The information distortion of a single ray is mainly caused by the use of randomly selected numbers in RMC method. In this paper, a finite volume and back ray tracing (FVBRT) method is put forward to provide definite rather than probabilistic description of the radiative transfer process. Accuracy of the FVBRT method is validated by comparisons with measured data, solutions of RMC method as well as results in the known literature. Considering compatibility with FVBRT method, the validated NBK model is chosen to formulate properties of non-gray gases. Finally, the FVBRT method and NBK model are coupled together to calculate IR signature of an aircraft, including the spatial distributions of radiative intensity and the IR images. The necessary absorption coefficients for NBK model are calculated from the spectroscopic database HITEMP 2010 in advance, and all the IR calculation process in this paper is accomplished via C program.

2. Numerical method for gas radiation

2.1. Radiative transfer equation (RTE) and narrow band k-distribution (NBK) model

In absence of scattering, the RTE is written as [25]

$$\frac{dL_\eta}{d\vec{s}} = k_\eta(L_{b\eta} - L_\eta) \tag{1}$$

where L_η is spectral radiance in the direction $\vec{s}$, η wavenumber, $L_{b\eta}$ spectral radiance of black body and k_η spectral absorption coefficient which depends on the local temperature, total pressure and gas mole fraction [26,27]. Boundary condition subject to Eq. (1) is expressed as

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

in which ε is the wall's emissivity and $\vec{n}$ is the corresponding surface normal vector. Eq. (2) depicts that spectral radiances leaving the wall boundary include two parts: emission of the wall itself and reflection of the spectral radiances from surrounding environment. It is necessary to note that Eq. (2) is only an implicit constraint since spectral radiances from the surroundings are also unknown variables to be solved.

To describe the radiative properties of non-gray gases, the narrow band k-distribution (NBK) model is used in this paper [28]. In the spectral interval of NBK model, the Planck function is treated as a constant and the spectral radiance is only determined by gas absorption coefficient in Eq. (1). The fundamental idea of NBK model is to convert the irregularly distributed absorption coefficients into a monotonically increasing form by introducing a cumulative distribution function $g(k)$. The integration over wavenumber space is then turned into an integration over g space, which can be performed conveniently by using a Gauss quadrature scheme. The RTE and average spectral radiance are then expressed as:

$$\frac{dL_g}{d\vec{s}} = k_g(L_{b\eta} - L_g) \tag{3}$$

$$\overline{L_\eta} = \frac{1}{\Delta\eta}\int_{\Delta\eta} L_\eta d\eta = \int_0^1 L_g dg = \sum_{i=1}^{N}\omega_i L_{gi} \tag{4}$$

in which N is the number of quadrature points, ω_i the quadrature weight and L_{gi} the corresponding radiance in Eq. (3). In this paper, the narrow band is set as 50 cm^{-1} wide (except where noted) and a 7-point Gauss quadrature scheme is adopted.

Under LBL approach, the integration process in Eq. (4) is realized by dividing $\Delta\eta$ into many sufficiently small intervals to ensure the detailed knowledge of every gas spectral line can be recognized. The spectral radiance is then solved in each small interval and summarized as

$$\overline{L_\eta} = \frac{1}{\Delta\eta}\int_{\Delta\eta} L_\eta d\eta = \frac{1}{\Delta\eta}\sum_{i=1}^{M} L_{\eta,i} d_{\eta,i} \tag{5}$$

in which M is the number of small intervals and $d_{\eta,i}$ is the length of every small spectral interval. Provided the wavenumber resolution is 0.01 cm^{-1}, then RTE needs to be solved 5000 times for LBL method in Eq. (5), but only 7 times for NBK model in Eq. (4). Besides the spectral radiance, other radiative properties such as band transmissivity and emissivity can also be calculated by the NBK model.

2.2. Validation of the NBK model

The NBK model is used to calculate band emissivity and transmissivity of CO_2 that have been measured in relevant Refs. [29–31]. Table 1 shows the conditions at which the measurements were performed.

The measured emissivities as well as calculated results by different methods are shown in Fig. 1(a) while Fig. 1(b) corresponds to the computational error defined as $(\varepsilon - \varepsilon_{\text{measured data}})/\varepsilon_{\text{measured data}}$. In Fig. 1(b), absolute errors of both NBK model and LBL method are less than 0.06. More importantly, the results of NBK model coincide with LBL data very well with a smaller computational effort.