Study on a calculation model of infrared radiation characteristics of rocket engine plume

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Abstract. In order to study the infrared radiation (IR) characteristics of rocket engine plume in the mid infrared band, a calculation model for IR transfer of rocket engine plume was built. The flow field data are calculated by software FLUENT. Based on HITRAN database, the IR characteristic parameters are calculated after spectral line correction. The Line of Sight (LoS) is used to solve the radiation characteristics in the plume flow field, and the IR characteristics distribution of the plume in the mid infrared band is obtained, which agree well with the results from open literature. The method has the advantages of simple model, less parameters and fast calculation speed in this paper.

1. Introduction

During the working process of the rocket engine, a large number of high-temperature and high-speed gas is produced. The tail flame emits a large amount of strong IR to the space, and the radiation intensity is mainly concentrated in 3-5 μm band[1]. The IR characteristic of engine plume is an important signal characteristic and detection mode of aircraft, especially in the middle and late stage of rocket flight. On the one hand, the IR intensity in the mid infrared region can be used as the monitoring index of orbit transfer engine fault. On the other hand, the IR characteristics reduce the overall stealth performance, and it is easier to become the target of military reconnaissance[2]. Therefore, studying the IR characteristics of rocket engine plume is helpful to better monitor the working state of rocket engine and improve the design of rocket engine[3, 4].

There are three main steps in the study of IR characteristics[5]: The first is calculation of flow field. The test conditions of rocket engine are strict and test cost is high. It is difficult to obtain the relevant data of flow field accurately. In this paper, a geometric model is built for the nozzle and tail flame area of orbit transfer engine. The flow field data are calculated by software FLUENT to obtain the parameters such as temperature, pressure and composition; The second is calculation of the gas radiation characteristics in flow field. Based on HITRAN database[6], the gas radiation characteristic parameters are obtained after correcting the spectral line, and the gas absorption coefficient is calculated by narrow band model; Finally, the IR transmission process is calculated. Through the LoS, the infrared transmission calculation model of rocket engine plume was built. In order to obtain the maximum characteristic information, the medium infrared was selected for infrared research. The IR characteristic distribution map within 3.2-5.5 μm band was calculated, and the IR characteristic data were analyzed.
2. Physical model of the plume flow field

2.1. Basic governing equations of flow field

The fluid must satisfy the law of conservation of mass, which is given as,

$$\frac{\partial \rho}{\partial t} + \text{div} (\rho \vec{u}) = 0$$  \hspace{1cm} (1)

Where $\rho$ is the density; $t$ is the time; $\vec{u}$ is the velocity vector.

The rate change of momentum in the fluid microelement over time is equal to the sum of various external forces acting on the fluid microelement. The momentum conservation equation is given as,

$$\frac{\partial (\rho \vec{u})}{\partial t} + \text{div} (\rho \vec{u} \vec{u}) = -\frac{\partial p}{\partial x} + \frac{\partial \tau_x}{\partial x} + \frac{\partial \tau_y}{\partial y} + \frac{\partial \tau_z}{\partial z} + F$$  \hspace{1cm} (2)

Where $p$ is the pressure on the fluid microelement; $\tau_x$, $\tau_y$, $\tau_z$, etc. are the components of viscous stress acting on the surface of fluid microelement due to molecular viscosity, Pa; $F$ is the external volume force on the micro element.

The energy conservation equation is the expression of the first law of thermodynamics. The energy conservation equation is given as,

$$\frac{\partial (\rho T)}{\partial t} + \text{div} (\rho u T) = \text{div} \left[ \frac{k}{c_p} \text{grad}(T) \right] + S_T$$  \hspace{1cm} (3)

Where $T$ is the temperature; $k$ is the heat transfer coefficient of the fluid; $c_p$ is the specific heat capacity of the fluid; $S_T$ is the viscous dissipation term.

The plume flow field belongs to high Reynolds number turbulence, and the turbulence effect needs to be considered. Research shows that the $k$-$\varepsilon$ turbulence model have good adaptability and stable convergence, and the numerical calculation can get ideal results\cite{7}.

2.2. Flow field calculation results

Combined with mass, momentum, energy conservation equation and $k$-$\varepsilon$ model, the temperature and composition of gas were obtained by FLUENT. Main gas phase components of the flow field are shown in table 1. The table shows that contents of CO$_2$ and CO are almost equal.

| Table 1. Main gas phase product components. |  |
|------------------------------------------|---|
| Gas composition | mass fraction |
| H$_2$O | 0.1018 |
| CO$_2$ | 0.0403 |
| CO | 0.0485 |
| N$_2$ | 0.6572 |
| H$_2$ | 0.0039 |
| O$_2$ | 0.1437 |
| Other components | 0.0046 |

The flow field was divided by O-grid, and the division results are shown in figure 1. After solving the equations under given conditions and considering the interaction between components, the
concentration distributions of the main gas components H$_2$O, CO$_2$ and CO in the plume flow field are obtained, as shown in figure 2 to figure 4.

Figure 1. Flow field grid diagram. Figure 2. Concentration distributions of H$_2$O.

Figure 3. Concentration distributions of CO$_2$. Figure 4. Concentration distributions of CO.

3. Calculation model of IR transmission based on Line of Sight

3.1. Calculation of gas radiation characteristic parameters

When the parameters of each spectral line could not be obtained in detail, the calculation of the average absorption coefficient in the spectral band needs to fit the relevant empirical parameters through experiments. Based on HITRAN database, according to the method given by Young[8], the absorption coefficient can be obtained as,

$$\bar{\kappa}_i = \frac{1}{\Delta \eta_i} \sum_{m=1}^{M} S_i^m$$  \hspace{1cm} (4)

Where $\Delta \eta_i$ is the wavenumber interval; $M$ is the total number of spectral lines; $S_i^m$ is the intensity of the $m$-th spectral line.

The absorption coefficient of the mixed gas is: $\kappa = \sum_{i=1}^{l} \bar{\kappa}_i$, $l$ is the number of gases.

3.2. Correction of spectral lines

In rocket engine plume, the pressure and temperature of the environment were non-standard. Based on the spectral line intensity in the atmosphere at $P_0=1$atm, $T_0=296$K provided by HITRAN database,
conversion result of spectral line intensity in non-standard state from spectral line intensity in standard state is obtained according to the conversion formula.

\[
S_q(T) = S_q(T_0) \frac{Q_{total}(T_0)}{Q_{total}(T)} \exp \left[ c_2 E^\eta \left( \frac{1}{T_0} - \frac{1}{T} \right) \left( 1 - \exp(-c_2 \eta / T) \right) \right] \tag{5}
\]

Where \( S_q(T) \) and \( S_q(T_0) \) are spectral line intensity of temperature \( T \) and reference temperature \( 296K \); \( \frac{Q_{total}(T_0)}{Q_{total}(T)} \) is the total partition function ratio, which can be approximated as a cubic polynomial function; \( E^\eta \) is low state energy; \( \eta \) is the wave number; \( c_2 \) is the second radiation constant.

### 3.3. Line of Sight

The ray path was divided into \( N \) layers along the direction passing through flow field, and the medium of each layer was considered to be uniform and isothermal. IR intensity of the ray can be obtained by recursion layer by layer until it leaves flow field[9]. The principle is shown in figure 5. Without considering the scattering, LoS method can directly use flow field data without remeshing.

![Figure 5. Schematic diagram of LoS.](image)

Considering the absorption and emission of each layer, the differential form of radiative transfer equation is,

\[
\frac{dI^{(l)}(s)}{ds} = \kappa_{ad} I^{(l)}(s) - \kappa_{sc} I^{(l)}(s) + \kappa_{sc} \frac{\kappa_{sc} \Phi^{(l)}(\Omega, \Omega)}{4\pi} I^{(l)}(s, \Omega) d\Omega \tag{6}
\]

Where: \( I^{(l)}(s) \) and \( I^{(l)}(s) \) are the spectral radiation intensity in direction \( \Omega \); \( \kappa_{ad} \) and \( \kappa_{sc} \) are the absorption coefficient and scattering coefficient; \( I^{(l)}(s, \Omega) \) is spectral radiation intensity in direction \( \Omega ; \Phi^{(l)}(\Omega, \Omega) \) is the scattering phase function.

Ignoring the scattering term, simplifying and introducing the optical thickness \( \tau^{(l)} = \kappa_{ad} s \approx \kappa_{sc} s \), the radiation recurrence formula along the LoS direction can be obtained as,

\[
I_0 = I_0^{-1} I_1 + I_{bd} (1 - \tau^{(l)}) \tag{7}
\]

The number of layers of each line in the grid, the thickness of each layer and the corresponding gas characteristic parameters need to be calculated firstly. Then the radiation intensity of all rays is calculated by the formula according to field angle. For less calculation, only the radiation intensity of the center is calculated as the average radiation intensity, and the error caused by simplification can be maintained within an acceptable range. The calculation flow is shown in figure 6.
4. Calculation results of IR

The IR is related to the gas composition in flow field. The spectral line absorption coefficient of the gas in 3.2-5.5 μm band is obtained from HITEMP database. CO₂ and CO have strong radiation ability in the mid infrared band, and radiation peak is in 4.2-4.4 μm and 4.5-4.9 μm range, as shown in figure 7 and figure 8.

According to the model, the IR characteristics in 3.2-5.5 μm band were calculated. The IR has peaks in 4.2-4.4 μm and 4.5-4.9 μm range, which is basically consistent with the peak value of gas radiation. Due to the example in this paper is different from the literature[10], the variation of radiation intensity with wavelength was compared after normalizing the two results, as shown in figure 9. It can be seen from the figure that variation trend of radiation intensity in this paper was basically the same as that in the literature[10]. In 4.5-4.9 μm range, the result in this paper is slightly more than that in the literature[10], which is due to the higher ratio of CO to CO₂ in this paper than in the literature[10].
5. Conclusion
In this paper, the IR calculation model of rocket engine plume is built based on LoS by using flow field data directly after correcting the spectral line, and the variation curves of IR intensity in mid infrared band is obtained. The results suggest that the model is accurate and reliable. The model in this paper is simple and requires less parameters. It can quickly calculate the plume IR characteristics in mid infrared band based on existing database, which not only provides a reference for the study of the IR characteristics of orbit transfer engine, but also provides an effective method for finding the working state of orbit transfer engine in time and accurately.

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