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Original research article

Analyzing the ultraviolet radiation of hydroxyl radical chemiluminescence in a motor plume using improved local equilibrium method coupled with Monte Carlo method

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ABSTRACT

Because of high false alarm rate of the infrared equipments, ultraviolet warning technology arouses greater attention. In this paper, a method of calculating hydroxyl (OH) radical chemiluminescence in a motor plume is put forward combining the improved Local Equilibrium method with the Monte Carlo method (iLEMC). The simulation method is validated by testing a hydrogen-oxygen engine. Meanwhile, comparison is made between the local equilibrium method and the improved local equilibrium method. The results suggest that the iLEMC method is accurate and efficient and the ultraviolet radiation of the plume is mainly from the OH radical chemiluminescence. These conclusion and results will greatly helpful for analysis, design and optimization of the UV warning systems and also the technique of UV stealth for aircrafts.

1. Introduction

Due to the advantages of strong adaptability, low false alarm rate, no refrigeration, small size and light weight, the ultraviolet (UV) warning equipments working in the "solar blind" region have developed into one of the largest installed missile warning systems [1–3]. For analysis, design and optimization of the UV warning system, there are important significance of researches on the UV radiation characteristics of the aircraft motor exhaust plume. Hydrogen-oxygen engine, one of the liquid motor, which has features of high performance, large trust and reliability, is the main power plant of the liquid ballistic missiles and launch vehicles and also space-crafts [4–6].

The exhaust plume of a hydrogen-oxygen rocket engine consists of high temperature gases. The products of the chamber are injected into atmosphere through the nozzle entraining the O_2, CO_2, CO and other gases in the atmosphere to carrying out the secondary combustion. The UV radiation of the plume is mainly from the chemiluminescence of the secondary combustion. Generally, the matters which give off UV radiation in the chemiluminescence processes are OH*, CH*, C_2* and CO_2* (The superscript "*" indicates the excited state). However, in the case of few carbon and hydrogen, the UV radiation of the latter three can be neglected. Davis et al. measured the OH radiation intensity, the temperature, and the OH concentration as a function of the height above the face of a premixed H_2/O_2 flat flame burner [7]. The conclusion was found that reaction mechanisms that could produce chemiluminescent OH radiation from the hydrogen-lean flames consistent with those obtained in hydrogen-rich flames. Lyons et al. summarized the calculation method of low altitude missile exhaust radiation

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in the visible and ultraviolet region of the spectrum [8]. They pointed out that OH radical and CO + O chemiluminescence were the sources of the exhaust plume UV radiation . The reaction equations and reaction rates of the two chemiluminescence processes were given in the article. The band model and the empirical formula were employed to calculating the chemiluminescence intensity. Hldaka et al. [9] found in the shock tube that, at the temperature range of 1200–3200 K, the reaction mechanism producing OH^* is:

$$H+O + M \rightarrow OH^* + M \quad (I)$$

Levin et al. calculated the UV radiation from hypersonic flows which considered the processes of collision, pre-dissociation, radiative decay and vibration energy exchange [10]. Vitkin studied the numerical physics model of a rocket plume [11]. The UV chemiluminescence mechanism in the literature included

$$H+OH+OH \rightarrow H_2O+OH^* \quad (II)$$

and two radiative decay reactions. The local equilibrium hypothesis was put forward to calculate the population of the OH^*. Wright et al. experimentally obtained the multi-bands images of the Atlas rocket at flight condition [12]. The experimental data was compared to simulation data in which it is assumed that the population of OH^* conforms to Boltzmann distribution. Plastinin et al. neglected the collision processes [13]. An assumption was made that at pressures and temperatures typical for the plume condition, population of the excited state must result from two-body recombination of O, H and from various three-body recombination reactions. The level de-excitation was supposed to result from pre-dissociation, radiative decay and various collisional processes. A shock tube experiment was conducted at temperature range of 1100–3000 k by Bozkurt et al [14]. It is verified that the mechanisms producing OH^* is Reaction (I). And the reaction rate was deduced. Fiala studied the chemiluminescence of the hydrogen-oxygen flames and the relationship between radiation and particles in excited state [15]. It came to a conclusion that at high temperature the square of the OH^* population was proportional to the radiation intensity, and at low temperature the decay processes should be considered.

All these lead up to the conclusion that the UV radiation of a hydrogen-oxygen engine plume is mainly from OH radical chemiluminescence. But the specific mechanisms are not conclusive. Reactions (I) and (II) are the well-known excited reactions and the other reactions are still under discussion. In this paper, based on the previous study, the OH radical UV radiation model which is developed from local equilibrium method is established. In simulation calculation, the Monte Carlo (MC) method is used to calculate the radiation transfer problem. Although MC method takes more time than other methods, it avoids solving the complex radiation transfer equation (RTE). Benefit from the greatly improvement of the computer performance, the calculation time consuming is within an acceptable range. The other methods, likes Discrete Ordinate Method (DOM) and Finite Volume Method (FVM), are simplifying the RTE in some degrees as a result that the solutions are not exact. Combining the improved Local Equilibrium method and the Monte Carlo method, there is the improved Local Equilibrium Monto Carlo (iLEMC) method. Detailed comparisons are presented with experimental spectral radiation intensity and spatial distribution of the radiation intensity at last.

2. Methods

2.1. Population of OH^*

In the hydrogen-oxygen engine exhaust plume, there are few H and H_2. The mass fraction of H_2 is about 10^{-2} while H is 10^{-3} or less. However, the atmosphere is rich in O_2. In hydrogen-lean flames the radicals are not in equilibrium with the stable products H_2O and O_2. They are, however, in equilibrium with each other owing to rapid and reversible bimolecular reactions. According to the local equilibrium hypothesis [7], the values of the concentrations of O, H and H_2 can be calculated from knowledge of the OH concentration. Considering Reactions (I) and (II) as the mechanisms producing OH^*, then the population changes of OH^* caused by the excited reaction is

$$\frac{d[OH*]_{exc}}{dt} = k_v \frac{K_2K_3}{K_1} \frac{[OH]^5}{[O_2]_e[H_2O]_e} + k_m \frac{K_2K_3^2}{K_1^2} \frac{[OH]^5}{[O_2]_e[H_2O]_e^2} [M] \quad (1)$$

where k_v and k_m are the reaction rate of Reactions (I) and (2) respectively and the values are from literature [13] and [14]. M indicates the reactions O_2, H_2, H_2O, CO_2, HO_2, CO, H and O. K_1, K_2, K_3 are the equilibrium constants [7]. The bracket means the population of the molecular or atom. The subscript "exc" means excited reaction and "e" means equilibrium state.

Since

$$\frac{d\,[OH*]}{dt} = 0 \quad (2)$$

for steady state conditions, then

$$[OH*] = \left(k_v \frac{K_2K_3}{K_1} [H_2O]_e + \frac{K_2K_3^2}{K_1^2} k_m\,[M] \right) \frac{[OH]^5}{[O_2]_e[H_2O]_e^2} \quad (3)$$

where k is the reaction rate of the corresponding reaction. This is the population of OH^* calculated by local equilibrium method.