The Plume Infrared Radiation Based on Visualization Computing

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ABSTRACT

The infrared radiation of plume has a great influence on the aircraft stealthy performance. The research of plume is mainly on plume modeling and plume infrared radiation calculation. To obtain a more vividly plume calculation process and more precise results, this paper combines the traditional geometric approximate modeling method and Curtis-Godson(C-G) approximate method by OpenGL to realize the plume infrared radiation visualization computing. A realistic plume model and an advanced C-G method are proposed. Two experiments results validate the effectiveness of this method.

KEYWORD: plume; infrared radiation; visualization computing

INTRODUCTION

With the rapidly development of aircraft, the research on aircraft technology attracts many people’s attention. And as an important part of aircraft, plume becomes a research focus. Plume is a kind of gas with high temperature (Chu & Xv, 2012). The radiation of plume is strong, and it plays an important part in aircraft stealthy performance (Laurel, 1968.). Furthermore, the infrared detection is the main detection ways as the plume is with high temperature (Rudman & Hibbeln, 2000). Therefore, it is essential for the researchers in related areas (e.g. aircraft stealth design, target tracking and recognition, etc.) to make an attention on the research of plume infrared radiation.

The research focus of plume infrared radiation is on plume modeling and plume infrared radiation calculation. For the plume modeling, a considerable amount of research has been done during the last decade. The method combining particle system and texture mapping (Zhu et al. 2008) can describe the color of plume in real time, but can not precisely describe the shape of plume. The method simulating the shape of plume by geometric approximate (Crow & Coker, 1996) can vividly describe the plume both in shape and color, but it is limited in describing the inner temperature distribution in real time.

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For the plume infrared radiation calculation, many studies have been conducted, and the absorption method and spectral band model are the mainstream methods. The absorption method (Dash et al. 1980) mainly concerns pure absorption parameter which needs to know the condition of each spectrum, and its accuracy is high but the calculated amount is huge. The spectral band model (Gao & Tang, 2007) is on the position and intensity distribution of each spectrum. In engineering, the Curtis-Godson (C-G) approximation based on spectral band is widely used, as the calculated amount is less and the accuracy can meet the requirements mostly. So far, the C-G method is under the assumption that the temperature distribution is homogenous in plume segment. However, in the actual situation, the temperature distribution is inhomogeneous. In this paper, an advanced C-G method is proposed which divides the plume segment into small areas according to the temperature distribution. To illustrate the results vividly, efficiently and quickly, we introduce the visualization computing (Fang et al. 2009). The main contributions are as follows:

(1) Based on Open Graphics Library (OpenGL), a plume modeling approach which combines geometric approximation and grid subdivision is proposed. By this approach, the shape and color of plume is described more finely. And the inner temperature distribution of plume is presented vividly. Also segmented display of the plume is realized.

(2) According to the temperature distribution of the plume, an advanced C-G method based on visualization computing is presented to achieve the plume infrared radiation computing. Two plume experiments’ results show that the proposed method is effective comparing with the reference data (Ludwig et al. 1973).

The remaining parts are organized as below. The plume modeling method using OpenGL is presented in Section 2. Advanced C-G method based on visualization computing is proposed in Section 3. The experiment results are shown in Section 4. The conclusion is summarized in Section 5.

PLUME MODELING BASED ON OPENGL

Plume is a complex gas radiation source. The shape and intrinsic parameter distribution is difficult to describe. In engineering applications, a simplified plume model is mostly used to calculate plume infrared radiation. The plume consists of two sections: initial segment and main segment. In initial segment, there is a part called core part with constant pressure and constant temperature which is with the highest temperature in the plume. As described in left of Figure 1, the shape of plume is a truncated cone, and the core part is a cone with the same bottom surface of the truncated cone.

![Figure 1. Schematic of plume model.](image)

To simulate the plume, we construct a plume model by OpenGL. The key steps are as below:
Firstly, the plume geometrical shape is built by OpenGL. In order to observe the inner temperature distribution and compute the infrared radiation characteristics of every direction, the cutting technology in OpenGL is used to divide the plume into different sections.

Secondly, mesh generation. To simulate the initial parameter more accurate, this paper makes mesh generation for the cut surface. According the temperature distribution in reference (Gao et al. 2007), this paper computes the temperature of some nodes. Then link four nodes by a quadrangle which temperature is determined by the mean value of the four corners, thus the cut surface is divided into many quadrangles. In the right of Figure 1, we can see the cut surface is consisted of many quadrangles.

Finally, draw artificial color map. To vividly describe the plume, this paper takes advantage of artificial color map which maps the temperature to color. The color is divided into a color map from red to blue. The number of dividing color is according to the requirement. Red represents the highest temperature while blue represents the lowest temperature. Other temperatures are represented by other colors according to the interpolation method. The artificial color map can not only describe the plume more vividly but also be useful in plume infrared calculation part. As described in the right of Figure 1, the cut surface is represented by the color quadrangles according to the temperature distribution.

To verify the proposed plume modeling approach, an example of plume model is given. The temperature distribution of the plume is achieved by the algorithm in reference (Gao & Tang, 2007). The plume parameters are as follows: the length of the plume is 1.0f, the length of core part is 0.25f, the radii of bottom are 0.25f and 0.8f, the side length of the quadrangle is 0.015f, the core part temperature is 935K, the temperature of final nozzle hot air flow is 288K, the pressure is 101325Pa.

Based to the temperature distribution, this paper designs an artificial color map and the corresponding relationship between temperature and color are shown in Table 1.

| Temperature | color R | color B | color G |
|-------------|---------|---------|---------|
| 273K        | 0.0     | 1.0     | 0.0     |
| 450K        | 0.0     | 1.0     | 1.0     |
| 600K        | 0.0     | 0.0     | 1.0     |
| 750K        | 1.0     | 1.0     | 0.0     |
| 935K        | 1.0     | 0.0     | 0.0     |

The image of plume model described by OpenGL is shown in Figure 2.

Figure 2 a is the whole model of plume and Figure 2 c is a section of plume, both of them are without mesh generation, while Figure 2 b and Figure 2 d are the model of plume with mesh generation and artificial color map, evidently, the model of plume in Figure 2 b and Figure 2 d is more vividly and fidelity.
ADVANCED C-G METHOD BASED ON VISUALIZATION COMPUTING

As the temperature distribution is captured, this paper takes advantage of an advanced C-G approximate based on spectral band method to compute the plume radiation computation. The C-G method divides the plume into some small enough sections where the temperature is the same to compute the plume infrared radiation.

In C-G method, the transmittance $\tau_\omega$ is given by

$$\tau_\omega = \exp(-\sum_i X_{\omega,i})$$

(1)

Where $i$ indicates the number of chemical components contributing to the plume radiation. $X_{\omega,i}$ denotes the optical depth at the wavenumber $\omega$ of the $i$th chemical component.

According to the given section or pathlength $u$, the optical depth through each position inside the plume can be described as

$$X = f(X^*, a_c, a_d)$$

(2)

Where

$$X^* = \sum_{n=1}^{n=\infty} k_n \Delta u_w.$$  

(3)

$$a_c = \frac{1}{X} \sum_{n=1}^{n=\infty} \left( \frac{\gamma_c}{d} \right) k_n \Delta u_w.$$  

(4)

$$a_d = \frac{1}{X} \sum_{n=1}^{n=\infty} \left( \frac{\gamma_d}{d} \right) k_n \Delta u_w.$$  

(5)

In equation (4)(5), the parameter $k$ is a band model parameter called absorption coefficient, and the parameter $1/d$ is also a band model parameter called line density. Both of them can be found in Reference (Ludwig et al. 1973). The parameter $\gamma_c$ is the collision half-width, and $\gamma_d$ is the Doppler half-width, which can be expressed as

$$\gamma_c = \left( \sum_j (\gamma_d^j)_{273} P_j \left( \frac{273}{T} \right)^{\gamma_d^j} + (\gamma_d^*)_{273} P \left( \frac{273}{T} \right)^{\gamma_d^*} \right)$$

(6)

$$\gamma_d = (5.94 \times 10^{-6}) \frac{p T}{M^{1/2}} \left( \frac{273}{T} \right)^{1/2}$$

(7)

Where $i$ refers to the radiating component under study and $j$ to the other chemical components of the sample in the plume; $p$ is the partial pressure; $M$ is the molecular weight of the radiating component under study; the other values can be found in reference (Ludwig et al. 1973).
Considering all the changes to the optical depth, it can be expressed as:

\[
f(X', a_r, a_d) = X' \left(1 - y^{-1/2}\right)^{1/2}
\] (8)

Where

\[
y = \left[1 - \left(\frac{X'}{X}ight)^2\right] + \left[1 - \left(\frac{X'}{X}ight)^2\right]-1
\] (9)

\[
X_r = X' \left(1 + \frac{X'}{4a_d}\right)^{1/2}
\] (10)

\[
X_d = 1.7 \cdot a_d \cdot \left\ln\left[1 + \left(0.589 \frac{X'}{a_d}\right)^2\right]\right\]^{1/2}
\] (11)

Then, the radiation can be expressed as

\[
L_{m,w} = -L_{b,m,w} \left[\tau_{m,w} - \tau_{m-1,w}\right]
\] (12)

Where, \(L_{b,m,w}\) is the radiation of black body, which can be expressed as

\[
L_{bb,m,w} = \frac{2\pi hc^2 w^4}{\exp(hcw/K_bT) - 1}
\] (13)

Where, \(h=6.626196 \times 10^{-34} \text{WS}^2\) denotes the Planck constant, \(c=2.997925 \times 10^{10} \text{cm/s}\) is the speed of light, \(K_b=1.380622 \times 10^{-23} \text{WsK}^{-1}\) denotes the Boltzmann constant.

According to the C-G method, the infrared radiation is only related to the temperature in the plume. And, as is shown in Section 2, the temperature distribution of the small areas in the section divided by C-G method is not the same. Thus this paper proposes an Advanced C-G method based on visualization computing. This method can be expressed as follows.

Firstly, compute \(L_{m,w}\) of each temperature of the plume section which can be represented by \(L_{m,w,n}\), where \(n\) denotes the temperature.

Secondly, count the area of each temperature occupied in the plume section according to Section 2. The area can be represented by \(S_n\).

Finally, the plume part infrared radiation \(L_{m,w}\) can be observed by equation

\[
L_{m,w} = \sum_{n=1}^{N} L_{b,m,w} * S_n
\] (14)

Where, \(N\) denotes the total number of temperature in the selected plume section.

After getting the value of \(L_{m,w}\), make a sum of all the sections radiation at each wave band which can be expressed as

\[
L_n = \sum_{w} L_{n,w}
\] (15)

**EXPERIMENTS**

Let’s take the infrared radiation of plume with a length of 60cm as an example. For simplify, the plume consists of only CO\(_2\). The pressure in the plume is the standard pressure (760mm Hg). According to method proposed in this paper, the plume is divided into 10 segments with a length of 6cm.

In this paper, as the available of line density parameter and absorption coefficient parameter are limited. For simplify, we take the approximate temperature for engineering requirement to improve the computation efficiency. Thus, for the temperature distribution in reference (Ludwig et al. 1973), the approximate temperatures can be given as:
300K, 600K, 900K, 900K, 1200K, 1200K, 900K, 900K, 600K, 600K

Making use of method proposed in this paper, we can achieve the infrared radiation of the proposed plume in the frequency range of the 2.7-µ band from the observation of the left side of the plume.

As it is illustrated in Figure 3, the simulated result of infrared radiation of plume by the method proposed in this paper agrees well with the result in the results in the reference (Simmons, et al. 1972). It verifies the correctness of the method proposed in this paper.

For inhomogeneous temperature situation, the inhomogeneous temperature areas can be divided into a number of homogeneous areas, we calculate the plume infrared radiation with some homogeneous segments step by step and sum up the infrared radiation. The temperature distribution data used in this example is taken from the example in Section 2. The plume is divided into 10 segments.

As it is illustrated in Figure 4, the peak of the result appears near 3500 cm⁻¹ which is coincided with the practical. The result can prove the correctness of the method proposed in this paper.

CONCLUSION

In this paper, by combining traditional geometric modeling and the C-G approximation, we conduct a visualization computing method of plume infrared radiation. The plume model is presented vividly and more precisely both in color and shape. Two experiments results validate the effectiveness of proposed method.

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