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Aero-optical effects in the hypersonic flow field

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Abstract : Aero-optical effects induced by the flow around the optical window degrade the performance of the IR seeker, especially for the hypersonic flow. For the thermochemical non-equilibrium flow, index of refraction model and optical transmission calculation method are developed to predict the aero-optical effects. The optical distortion is discussed for the typical optical widow shape and flow condition. The influence on aero-optical effects is analyzed.

Key Words : Aero-optical effects, Hypersonic, Non-equilibrium flow, Image distortion

1.Introduction

Aero-optical effects induced by the flow field around the IR seeker optical window are important problem in designing a interceptor[1]. When IR signatures from the target transmit throughout the hypersonic flow field, the imaging distortion, such as boresight error, blur and jitter, will be produced on the imaging sensor of the IR seeker. These effects degrade the precision of the interception severely and needed to be solved, especially for the hypersonic IR seeker[2].

In the research of the aero-optical effects for the IR seeker, most study is based on the perfect gas[3-5]. But for the hypersonic seeker the flow often is thermochemical non-equilibrium gas. This paper aimed at studying the aero-optical effects caused by the thermochemical non-equilibrium gas with the numerical method and some influencing factors on the optical distortion were discussed, for example, infrared window shape and incoming flow condition.

2.Numerical simulation of the flow field

The numerical simulation method for thermochemical non-equilibrium flow is developed. Multiple-species Navier-Stokes equations are solved to provide the density distribution and the flow species including O2, N2, NO, O and N[6].

$$\partial_t \, dV + \oiint_S (\vec{g} \cdot \vec{n}) dS = \frac{1}{Re} \oiint_S (\vec{h} \cdot \vec{n}) dS + \iiint_{\Delta V} \dot{\omega} dV)$$

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The chemical kinetics is modeled using Arrhenius finite rate reaction model where 5 species and 5 reactions are considered[7]. Convective terms are modeled by AUSM+ scheme in the second order accuracy in space integration[8]. For the time integration, lower-upper symmetric Gauss-Seidel (LU-SGS) scheme is applied[9].

3.Numerical simulation of the aero-optical effects

The numerical simulation of the aero-optical effects includes two steps: first step is the modeling for the index of refraction, the second step is the simulation of the optical distortion. The simulation of the optical distortion is studied by many researchers, so the emphasis of this paper is to get the modeling for the index of refraction.

3.1. The index of refraction model for non-equilibrium flow

Based on the electromagnetics and electrodynamics theory, the index of refraction for the single species is[10,11]:

$$\frac{n^2-1}{+2} = \frac{\varepsilon_r-1}{\varepsilon_r+2} = \frac{\rho}{M}\frac{a}{3\varepsilon_0}$$

where ρ is the density, M is the molecular weight, N_A is the Avogadro constant, a is the molecule polarizability.

For the most gas, its index of refraction is very near 1($n-1=O(10^{-4})$),so the index of refraction is approximated to

$$n-1 = \frac{N_A a}{2M\varepsilon_0}\rho = K_{GD}\rho$$

where K_{GD} is the G-D constant for the gas, which is conversion factor from density to index of refraction and is the relation between aerodynamics and the optics.

The molecule polarizability for the 5 species can be obtained from the gas database and the chemistry handbook. And then the G-D constant for each species is calculated.

Table. 1 Gladstone-Dale constant

N_2	O_2	CO	N	O
0.233	0.186	0.218	0.158	0.191

For the mixing gas, the index of refraction is expressed as

$$n-1 = K_i\rho_i$$

where K_i and ρ_i stand for the G-D constant and density for each species. The G-D constant for the mixing gas is

$$K_{GD} = \sum K_i\rho_i/\rho = \sum K_i a_i$$

where ρ is the density of the mixing gas, a_i is the mass fraction of the species. This two parameter can be obtained using the numerical simulation of the hypersonic flow.

3.2. Numerical simulation for optical transmission effects

The optical transmission effects can be separated as two parts: the optical transmission effects for the average flow and the optical transmission effects for the fluctuation flow. For the average flow, optical path difference is calculated by ray tracing method firstly and then the point spread function(PSF) and optical transmission function(OTF) are calculated by Fourier optics. For the fluctuation flow, the optical transmission function is calculated by autocorrelation of the optical phase difference, and then the point spread function is calculated by inverse Fourier transform[12].

The optical transmission effect for turbulent flow is the summation of the average flow and the fluctuation flow, the point spread function is expressed as:

$$SF\ x',y') = PSF\ \ (x',y')*PSF_T(x',y')$$

where * stands for convolution, PSF_M(x',y') is the point spread function for average flow, PSF_T(x',y') is the point spread function for the fluctuation.

4.Analysis of optical distortion

The aero-optical effects in the hypersonic flow field are simulated. The IR window is the typical dome window and the typical side plane window[3]. Figure 1 shows the optical window shape and its position. Table 2 shows the inflow condition. For the imaging system, the working wavelength is 3μm, the focal distance is 50mm and the pupil diameter is 30mm.

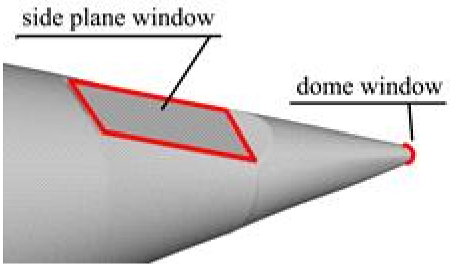


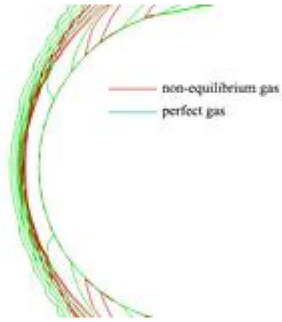
Fig. 1 Shape of the optical window(Ref.3)

Table. 2 Inflow conditions

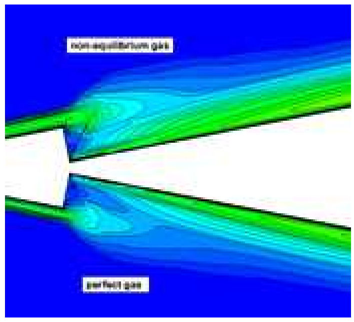
	Ma	h(km)	gas model
Case1	10	30	non-equilibrium gas
Case2	12	30	non-equilibrium gas
Case3	15	40	non-equilibrium gas
Case4	12	30	perfect gas

4.1. Influence of gas model on the optical distortion

The flow structure is different between non-equilibrium gas and perfect gas. Figure 2 shows the compare of density and density fluctuation scale for two gas models. The shock detached distance, the density behind the shock wave and scale of density fluctuation are different remarkably between the two gas models.



(a)isoline map of density



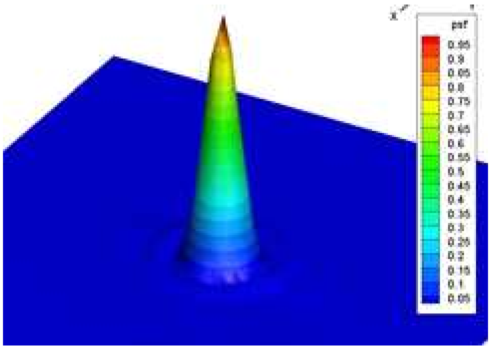
(b) contour map of density fluctuation scale

Fig.2 Flow field compare between two gas models

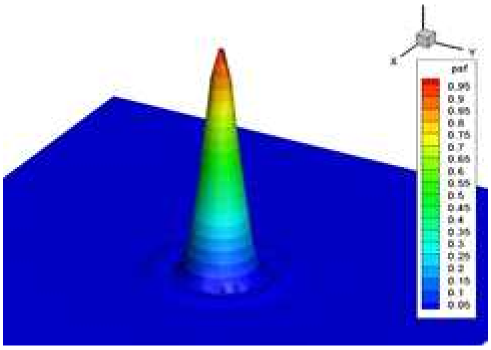
The optical distortions for the side plane window are show as table 3. It is shown that the optical distortion is slight for the perfect gas while it is obvious for the non-equilibrium gas. The optical intensity on the focal plane is shown as figure 3. The maximum of the intensity for the non-equilibrium gas is less than it for the perfect gas and the intensity is more dispersed.

Tabel. 3 Influence of gas model

	non-equilibrium gas (case2)	perfect gas (case4)
Strehl ratio	0.905	0.967
Contain energy diameter	1.37	1.05



(a) non-equilibrium gas



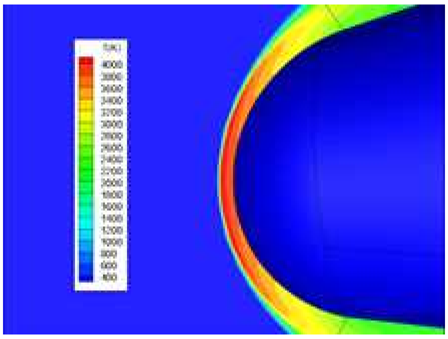
(b) perfect gas

Fig. 3 Intensity on the focal plane

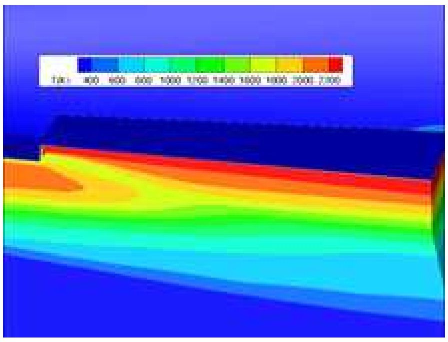
4.2. Influence of window shape on the optical distortion

Two types of IR window shape is discussed. one is the dome window on the head, the other is plane window on the side. In the case 2, the strehl ratio for dome window is 0.999, while it for the plane side window is 0.905. the conclusion is that when only the optical transmission effects is considered, the dome window is better than the side plane window.

But the infrared noise also can affect the imaging, which caused by the high temperature flow and the heated optical window. The Fig.4 shows the temperature of the flow field. The flow temperature around the dome window is about 4000K, while it around the side plane window is about 2000K. The estimation for the temperature increase of the optical window under aerodynamic heating shows that the dome window is about 1200K while the side plane window is about 550K. This means the infrared noise of the dome window is much more severe than the side plane window. The huge infrared noise could cause invalidation of the imaging system, so the side plane window is more suitable to the hypersonic IR seeker when the infrared noises is considered.



(a) dome window



(b)side plane window

Fig. 4 Flow temperature

4.3. Influence of inflow condition on the optical distortion

The optical distortion at different Mach number is analyzed. The results show that Mach number of the inflow is larger, the optical distortion is more severe, which means that the maximum of the optical intensity on the focal plane is lower and the optical intensity is more dispersed.

The optical distortion at different flight height is analyzed. When the height is more than 40km, because the density of the flow is very small and the nonuniformity of refraction index is trivial, the optical distortion can be ignored and the optical intensity approximates to no aberration condition.

Table. 4 Influence of inflow condition

	Strehl ratio	Contain energy diameter
Case1 (Ma10-h30)	0.944	1.17
Case2 (Ma12-h30)	0.905	1.37
Case3 (Ma15-h40)	0.998	1.01

5.Conclusion

The method is developed to simulate the aero-optical effects in the thermochemical non-equilibrium flow field. The influence of inflow condition on the aero-optical effects is analyzed. Mach number of the inflow is larger, the optical distortion is more severe. The height of the inflow is larger, the optical distortion is more slight. When the height is more than 40km, the optical distortion can be ignored and the optical intensity approximates to no aberration condition.

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