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Reentry Blackout Simulation Using CFD Combined with Radio Transmission Calculation

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Abstract

Multi-component flow field and radio blackout effects during the RAM C-II reentry flight are investigated using computation fluid dynamics (CFD) combined with two electromagnetic-wave propagation methods. The flow field is simulated using chemical non-equilibrium Navier-Stokes equation by AUSM+ scheme. The chemical reaction dynamics are simulated using a 7-species-7-reaction and a 11-species-20-reaction models. After electron density is obtained, radio transmission and attenuation are simulated using the Wentzel-Kramer-Brillouin (WKB) and Finite Difference Time Domain (FDTD) methods, for 4 frequency bands, i.e., L-band, S-band, C-band and X-band. Blackout is diagnosed using the criterion that the radio attenuation reaches 30dB. The simulation results are compared with the flight test data. The comparison indicates that the 7-species chemical reaction model cannot correctly predict the electron density in the plasma sheath, while the 11-species model gives good prediction down to the altitude 56.39km, after where the beryllium cap was ejected and the flow started to be polluted by alkali-metal ablation products. FDTD method gives good predictions to radio attenuation and hence to blackout altitude while the WKB prediction of the onset of blackout is earlier than FDTD and flight test results.

Keywords: *blackout, reentry, chemical non-equilibrium, plasma, radio attenuation*

Nomenclature

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Latin
C_p – Specific heat at constant pressure
e_{ve} – vibration energy
h – Static enthalpy
H – Total enthalpy
k – Thermal conductivity
M – Mach number
N_e – Electron density
p – Pressure
Pr – Prandtl number
T – Temperature
u, v, w – velocity in x, y, z directions

Greek
γ – Ratio of specific heats
μ – Viscosity coefficient
ν – Kinematic viscosity
ρ – Density
τ – Shear stress
ω – source term

Subscripts
i – ith specie
∞ – Free stream conditions t

1. Introduction

During the reentry of orbital vehicles, very high speed can be reached. The strong shockwave formed in front of the vehicle and the intense friction between the vehicle and surrounding air make the temperature rise sharply, leading to dissociation and ionization of the surrounding air. This process forms around the vehicle a high-temperature plasma sheath, which attenuates and reflects the radio signal, resulting in the failure of communication between the vehicle and ground, which is called the "radio blackout". The radio blackout cuts off all kinds of radio signals including navigating, telemetry, vehicle tracing, etc., and is a main threaten to the flight task.

Large efforts have been make to alleviate the blackout during reentry. To investigate the formation and alleviation of blackout, several hundreds of flight tests have been carried out since 1950s. Among these there is RAM (Radio Attenuation Measurements) program [1], carried out by NASA, which included 7 successful flight tests and lasted for nearly 10 years. Many of the present blackout alleviation methods, such as water injection and electrophilic material injection, were tested in this program. However, these methods still cannot be used in reality. Prohibitively high cost of flight test makes further optimization of these methods difficult. Using numerical tools to simulate the blackout phenomenon, the research cost can be greatly reduced, and may help find feasible method for blackout alleviation.

2. Numerical methods

2.1. Chemical non-equilibrium flow simulation

The multi-component Navier-Stokes (NS) equation in 3-d Cartesian coordinate system is:

$$\frac{\partial Q}{\partial t}+\frac{\partial E}{\partial x}+\frac{\partial F}{\partial y}+\frac{\partial G}{\partial z}-(\frac{\partial E_v}{\partial x}+\frac{\partial F_v}{\partial y}+\frac{\partial G_v}{\partial z})=S \tag{1}$$

Where $Q = [\rho_1,\ldots\rho_{ns}, \rho u, \rho v, \rho w, \rho E, \rho e_{ve}]^T$ is the state vector, E, F, G and E_v, F_v, G_v are the inviscid and viscid fluxes in x, y, z directions, and $\boldsymbol{S}$ is the source term vector. The chemical reaction dynamics is modelled using Gupta's model [2]. The 7-species model contains O, N, O_2, N_2, NO, NO^+ and e^-, the 11-species model further contains N^+, O^+, N_2^+ and O_2^+.

The equation is solved on a multi-block structured grid using a Finite-Volume (FV) code. The inviscid fluxes are calculated using the AUSM PW+ scheme and the viscid fluxes using the central scheme. The LU-SGS method is used for implicit time advancement.

2.2. FDTD method

The FDTD method solves the Maxwell equation

$$\nabla\times H = J+\varepsilon\frac{\partial E}{\partial t}$$
$$\nabla\times E = -\mu\frac{\partial H}{\partial t} \tag{2}$$

on the calculation grid set up in the position of the antenna. The distribution of the plasma electron density obtained from the NS equation is interpolated to the calculation grid of electromagnetic wave. Yee's grid is used as the calculation grid. In the Yee's grid, the components of the electric field and the magnetic field are intersecting in the space, so that each of the electric field components is surrounded by magnetic field components, and each of the magnetic field components is surrounded by electric field components. Thus the continuity condition of field components on the surface of any sudden change surface can be satisfied naturally.

From the electron motion equation

$$m_e \frac{\partial (n_e \boldsymbol{v})}{\partial t} = -n_e e E - \nu_c m_e n_e \boldsymbol{v} \tag{3}$$

there is the control equation of electricity current $\boldsymbol{J}$:

$$\frac{\partial \boldsymbol{J}}{\partial t} + \nu_c \boldsymbol{J} = \varepsilon_0 \omega_{\mathrm{pe}}^2 \boldsymbol{E} \tag{4}$$

where $\nu_c = \nu_{c0} p / p_0$ ($\nu_{c0} = 4.4\times10^7$ Hz, p_0 = 1Pa) is the collision frequency between the electron and neutral particles, and $\omega_{\mathrm{pe}} = [n_e e^2/(m_e \varepsilon_0)]^{1/2}$ is the plasmas frequency.

A given incident wave is given to calculate the waveform and intensity of the reflection and transmission. Since the ground signal is far away from the receiving antenna on the vehicle, it can be seen as a plane wave at the receiving antenna. The transmission coefficient of electromagnetic waves at different frequency bands through the plasma sheath is calculated at different altitudes.

2.3. WKB method

Assume the 1-d situation: the plasma is only inhomogeneously distributed in the direction normal to the wall, which is also the transmission direction of radio signal. The thickness of plasma layer is d. Suppose the electric field is in y-direction and magnetic field in z-direction, the WKB solution of Maxwell equation (2) is

$$E_y = E_{y0} \exp\left(j \int_0^z k dz' \right) \tag{3}$$

where $k = k_0 \sqrt{\varepsilon_r} = \frac{\omega}{c} \sqrt{\varepsilon_r}$ is the wave number of radio wave in plasma, k_0 the wave number of radio wave in vacuum, ε_r the relative dielectric constant, and ω the angular frequency of radio wave. The power of the electral-magnetic wave reaching z=d is

$$P = P_0 \exp\left(-2\,\mathrm{Im}\left(\int_0^d k dz \right) \right) \tag{4}$$

where P and P_0 are the power at $z=d$ and $z=0$, respectively. Thus, the transmission T and attenuation Att can be calculated as

$$\begin{aligned} T &= \frac{P}{P_0} = \exp\left(-2\,\mathrm{Im}\left(\int_0^d k dz \right) \right) \\ Att &= -10\lg T = 8.686\,\mathrm{Im}\left(\int_0^d k dz \right) \end{aligned} \tag{5}$$

3. Simulation condition

3.1. Brief description of RAM C-II flight test data

The RAM C-II vehicle is a 9° half-angle blunt cone with a 15.24 cm radius hemispherical nose. A beryllium nose cap was used to prevent the production of ablation products from the early period of reentry down to 56.39 km, where the nose-cap temperature approached the melting point of beryllium. After that the nose cap was ejected and a Teflon nose of 3.81 cm radius was exposed. Reflectometers and electrostatic probes were used to measure the electron density in the plasma sheath.

3.2. Simulation conditions

The simulation conditions are summarized in Table 1.

Table 1. Simulation conditions

Altitude (km)	Speed (km/s)	Mach number
76	7.65	26.56
71	7.65	25.91
62	7.65	24.55
53	7.62	23.30
48	7.59	23.01
40	7.38	23.27
31	6.55	21.66
25	5.12	17.16

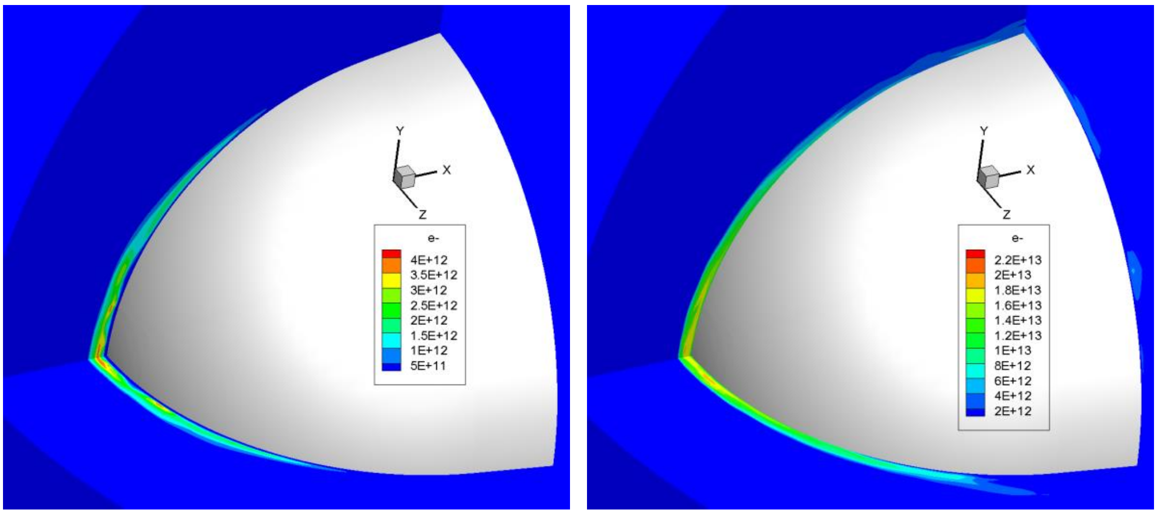
For each altitude, the chemical non-equilibrium Navier-Stokes equation is solved for the electron density.

Transmission and attenuation for the radio signal at the 4 frequency bands, namely L-, S-, C- and X-bands, are calculated using both the WKB and FDTD methods. The radio frequency of the calculated 4 bands are 1116, 3348, 5800 and 9210 MHz respectively. Blackout is diagnosed using the criterion that the radio attenuation reaches 30 dB.

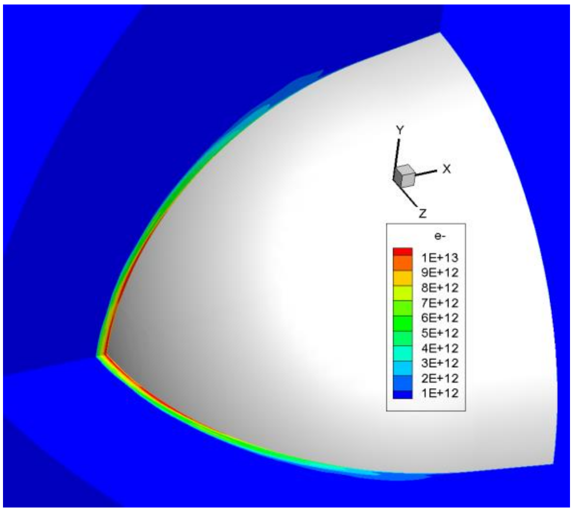
4. Results

4.1. Electron density distribution

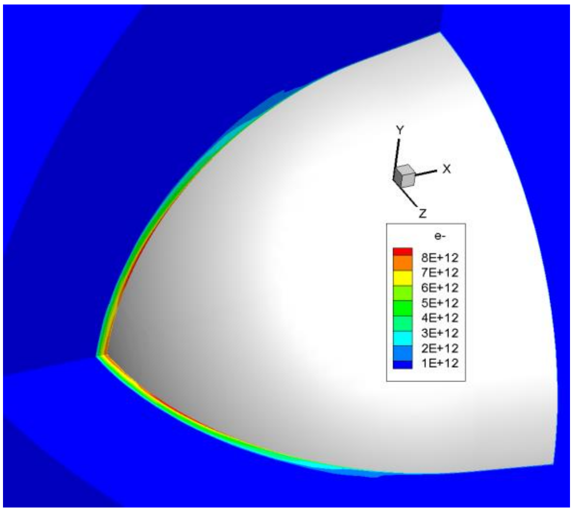
The electron density obtained using the 11-species model is of the order of 10^{12} at 76 km and 10^{13} between 53 and 71 km. These results compare well with the flight test data. The 7-species model underpredicts the peak of N_e by 2/3. Below 53 km both models fail to predict the further increase of N_e, which should exceed the order of 10^{14}. This is because below this altitude the beryllium cap was ejected and the flow started to be polluted by alkali-metal ablation products.



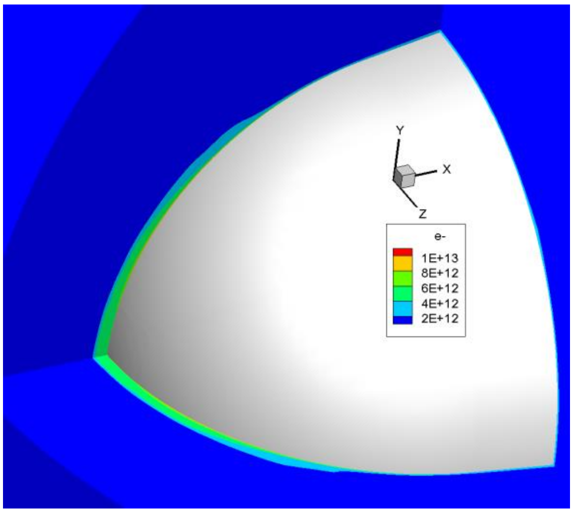
(a) 25km (b) 40km



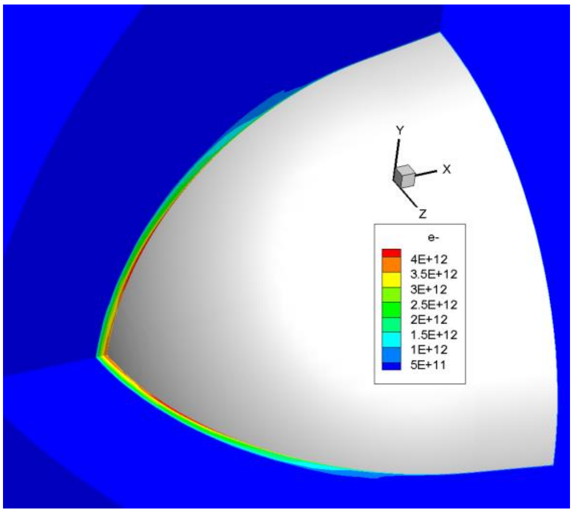
(c) 48km



(d) 53km



(e) 62km

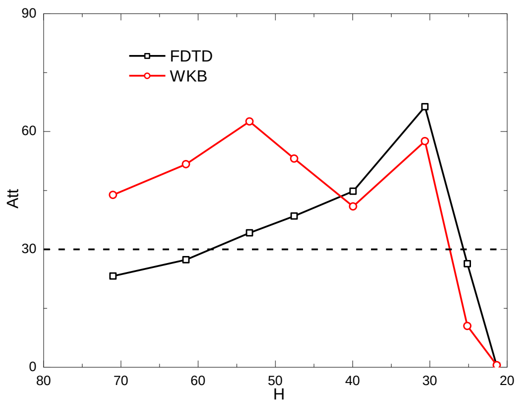


(f) 76km

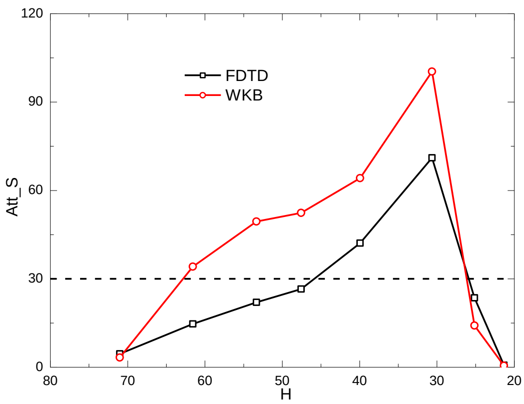
Fig 1. Distribution of electron density (cm-3)

4.2. Radio attenuation in plasma sheath

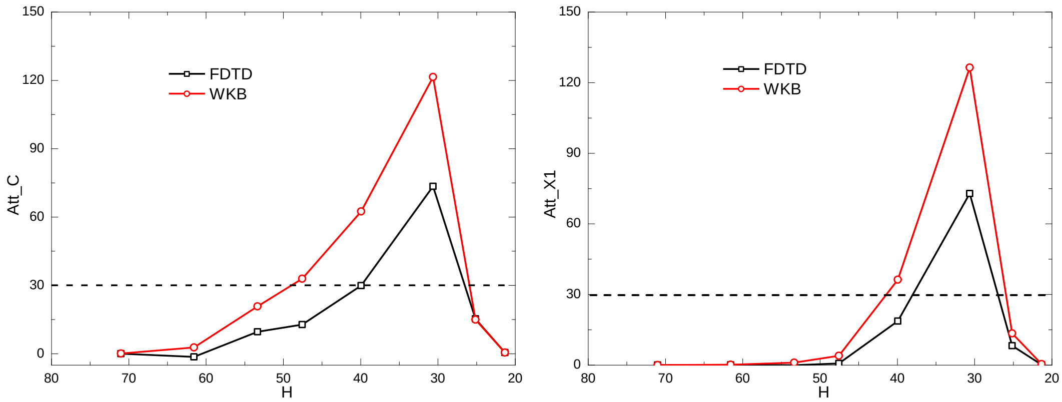
The radio signal attenuation predicted by WKB and FDTD methods are compared in Fig. 2.



(a) L band



(b) S band



(c) C band (d) X band

Fig 2. Radio attenuation obtained by FDTD and WBK methods

FDTD correctly predicted the onset of blackout for C- and X- bands, which is between 48 and 36 km. The WKB prediction of the onset of blackout is earlier than FDTD and flight test results. For the L-band and S-band the onset of blackout cannot be predicted due to under-prediction of Ne, which is a result of not considering the ablation products, as discussed in 4.1.

Table 2. Prediction of Blackout duration

Frequency Band	Blackout onset			Blackout end		
	Flight	**WKB**	**FDTD**	**Flight**	**WKB**	**FDTD**
L	----	----	62-53	----	31-25	31-25
S	----	71-62	48-40	----	31-25	31-25
C	48	53-48	48-40	----	31-25	31-25
X	36	48-40	40-31	----	31-25	31-25

5. Conclusion

CFD combined with two electromagnetic wave propagation methods, namely WKB and FDTD, are used for simulating the multi-component flow field and radio blackout effects during the RAM C-II reentry flight. The electron density distribution in the plasma sheath, formed around the vehicle during reentry, is calculated by solving the chemical non-equilibrium Navier-Stokes equation, with the chemical reaction dynamics modelled with either a 7-species-7-reaction model or a 11-species-20-reaction model. After electron density is obtained, radio transmission and attenuation are simulated using the Wentzel-Kramer-Brillouin (WKB) and Finite Difference Time Domain (FDTD) methods, for 4 frequency bands, i.e., L-band, S-band, C-band and X-band. Comparison between simulation results and flight test data indicates that the 11-species model gives good prediction down to the altitude 56.39 km, after where the beryllium cap was ejected and the flow started to be polluted by alkali-metal ablation products. FDTD method gives good predictions to radio attenuation and hence to blackout altitude while the WKB prediction of the onset of blackout is earlier than FDTD and flight test results. The current work shows that the presented method can be used in blackout prediction for non- alkali-metal flow conditions.

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