Numerical prediction of plasma formation on a sphere in hypersonic sub-orbital flight regime

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Abstract. Hypersonic flight is challenging for vehicle design and operation due to the intense heating generated by kinetic energy transfer from the vehicle to the gas surrounding it. As a result, plasma is produced, which can interfere with radar tracking and communication, particularly upon re-entry into the Earth's atmosphere. Plasma affects wave propagation, and if the electron density is high enough, waves may lose intensity as they propagate, distorting radar traces. The objective of this research is to predict plasma formation during suborbital hypersonic flight, with a specific focus on determining the Mach number and altitude conditions that generate critical levels of plasma density. To achieve this, Computational Fluid Dynamics is employed to solve the Navier-Stokes equations, and a multi-temperature thermochemical model is adopted to accurately predict plasma behavior. The model is applied in a simplified scenario involving a sphere exposed to hypersonic flow.

Introduction

The hypersonic regime is a flight condition that poses significant difficulties to flight vehicle design and operation. In hypersonic flight, objects traveling at speeds much higher than the speed of sound transfer a significant amount of kinetic energy to the gas surrounding them. This leads to an increase in the gas's internal energy and generates a region of high temperature around the body. The resulting gas flow characteristics are highly complex and differ from those observed in subsonic and supersonic flows. The transfer of kinetic energy from the object to the gas primarily occurs through an intense bow shock wave, which envelops the flying object. This phenomenon triggers chemical reactions and air ionization, leading to the formation of a plasma, which is a state of matter consisting of charged particles (i.e., ions and electrons) that interact strongly with electromagnetic fields. The plasma formed around the hypersonic vehicle can affect the vehicle's radio communication capabilities, produce electromagnetic interference, and significantly disrupt radar tracking, leading to the "blackout" phenomenon. In fact, the presence of a non-negligible number of ions and electrons around an object in its hypersonic motion can cause a significant reduction in electromagnetic wave transmission and reflection efficiency, leading to a complete loss of communication signals. This phenomenon can occur at any altitude but is most severe during re-entry into the Earth's atmosphere, where plasma formation around the hypersonic vehicle is the most pronounced. Therefore, understanding and predicting plasma formation around hypersonic vehicles is crucial. This would help evaluate their radio communication capabilities, obtain reliable data for radiation heating simulations, and accurately track such objects.

To go into further detail, if the density of charges is high enough in plasma, the wave can undergo complete reflection. The properties that govern wave propagation in a medium are defined by the relative electric permittivity ϵ_r or, alternatively, the refractive index (provided that the medium is non-magnetic). According to the standard theory [1], the refractive index n is related to the frequency f of the EM wave (e.g. one generated by radar) and the electron density n_e of the plasma according to the following relationship:

$$n^2 = \varepsilon_r = 1 - \frac{f_{pe}^2}{f(f+if_c)} = 1 - \frac{f_{pe}^2}{f^2+f_c^2} + i\frac{f_{pe}^2 f_c}{f(f^2+f_c^2)}. \tag{1}$$

the electron number density $\boldsymbol{n_e}$ is related through the plasma frequency:

$$f_{pe} = \sqrt{e^2 n_e/\varepsilon_0 m_e}. \tag{2}$$

where n_e is the number density of electrons, e is the electric charge, m_e is the effective mass of the electron, and ϵ the permittivity of free space.

f_c is the collision frequency (between electrons and neutral particles) defined as [2]:

$$f_c = \sum_i n_i \sigma_{i,e} \sqrt{\frac{8k_b T}{\pi m_e}}. \tag{3}$$

with n_i being the neutral density, $\sigma_{i,e}$ the neutral-electron cross section for the neutral species *i, T* the temperature and k_b the Boltzmann constant.

The real part of the refractive index becomes zero or negative when the frequency of the wave is lower or equal to the plasma frequency (f_{pe}), which occurs when the electron density is sufficiently high. In regions where the square of the refractive index is less than or equal to zero, the wave is classified as evanescent and gradually loses intensity as it propagates, leading to the reflection of the radiation by the plasma surface. This results in the replacement of the body surface by the plasma surface, causing a distortion in the radar trace. If the plasma density fails to reach the cut-off threshold of $\frac{f_{pe}}{f} > 1$, the phenomenon of refraction or absorption can still occur, leading to a redistribution of the electromagnetic waves and a decrease in re-radiation.

The real part of ϵ_r governs wave propagation, while the imaginary part determines collisional absorption (i.e. the transfer of energy from electrons to neutral species).

This research aims to create a reliable numerical model capable of predicting plasma formation in the context of suborbital hypersonic flight. More specifically, the aim is to determine the Mach number and altitude conditions that could generate regions surrounding the vehicle, where the value of $\frac{f_{pe}}{f}$ and $\frac{f_c}{f}$ reach critical levels.

Plasma model and methodology

Since the considered flight altitude is low, the fluid is approximated as continuous and is described by the Navier-Stokes equations. The Computational Fluid Dynamics approach is used as a means of solving these equations and predicting plasma behavior. In this study, air is a chemically reactive and compressible mixture comprised of seven chemical species: oxygen (O2), nitrogen (N2), nitric oxide (NO), nitrogen atoms (N), oxygen atoms (O), nitrous oxide ions (NO+), and electrons (e-). Given the presence of high temperatures, the modes of rotational, translational, vibrational, and electronic energy must be taken into account. For this reason, a multi-temperature model is adopted to describe energetic non-equilibrium phenomena. The thermochemical model utilized in this study is described in [2,3], and the thermodynamic properties of each chemical species are the ones specified in [4]. Additionally, diffusion coefficients for each chemical species are taken from [5].

Given the large computational cost of solving this complex problem, the model is applied to a simple axial-symmetric case of a sphere with a radius of $152.4\ mm$, exposed to a hypersonic flow.

The Mach number and altitude conditions correspond to the trajectories typical of a hypersonic Glider available in [6]. A radiative adiabatic wall condition has been applied at the wall

It should be noted that numerical and experimental results related to this type of simulation are very rare in the literature. Therefore, the model's validation becomes even more important. Specifically, experimental data obtained for the RAM-C II [7] will be presented to validate the developed model.

Results

The following results are reported for an interesting case, related to a flight altitude of 40 kilometres and a Mach number equal to 15. The plasma and collision frequencies have been scaled with respect to a reference frequency of 1 GHz. The compressive shock effect on the air generates high temperatures downstream, as observed in Fig.1. Additionally, the adiabatic radiative wall boundary condition causes the temperature at the wall to decrease. However, the most critical zone is where the shock is normal to the direction of the air, leading to considerable high-temperature effects. This observation is supported by Fig.2, which shows the largest concentration of electrons in this region. When examining the area near the axis of symmetry, numerical instabilities cause the shock to become slightly distorted.

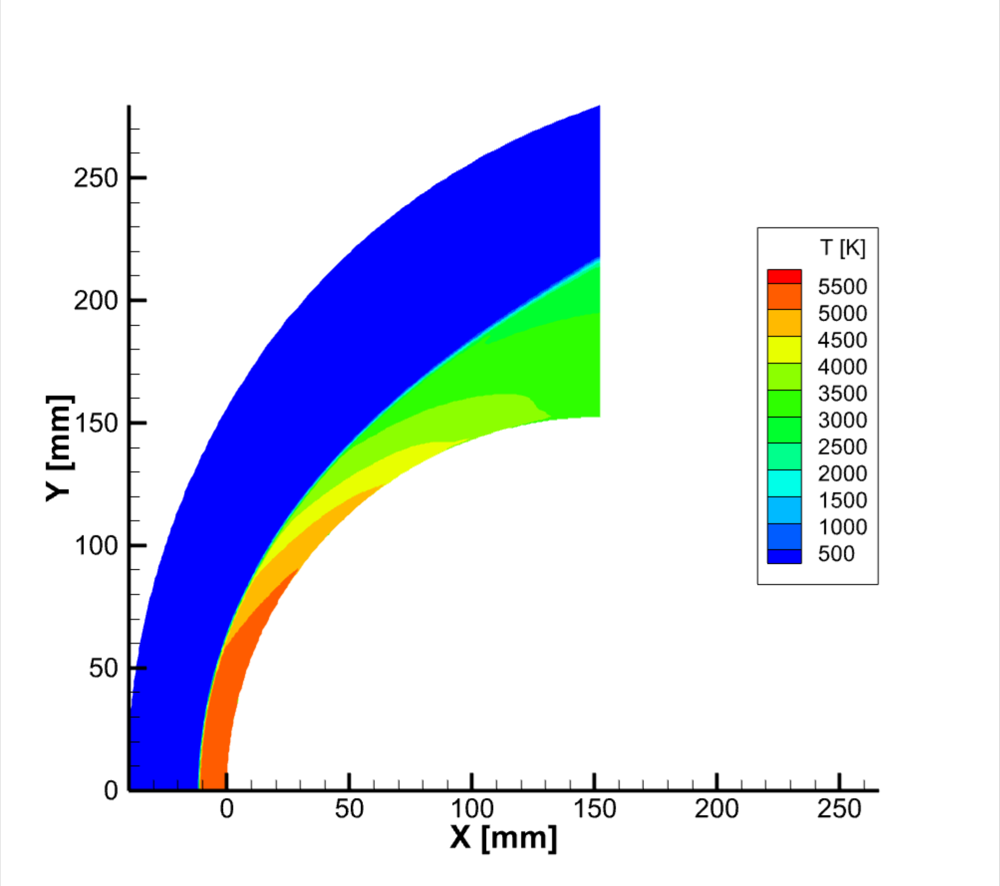

Fig. 1-Temperature around a sphere at an altitude of 40 kilometres at a Mach number of 15.

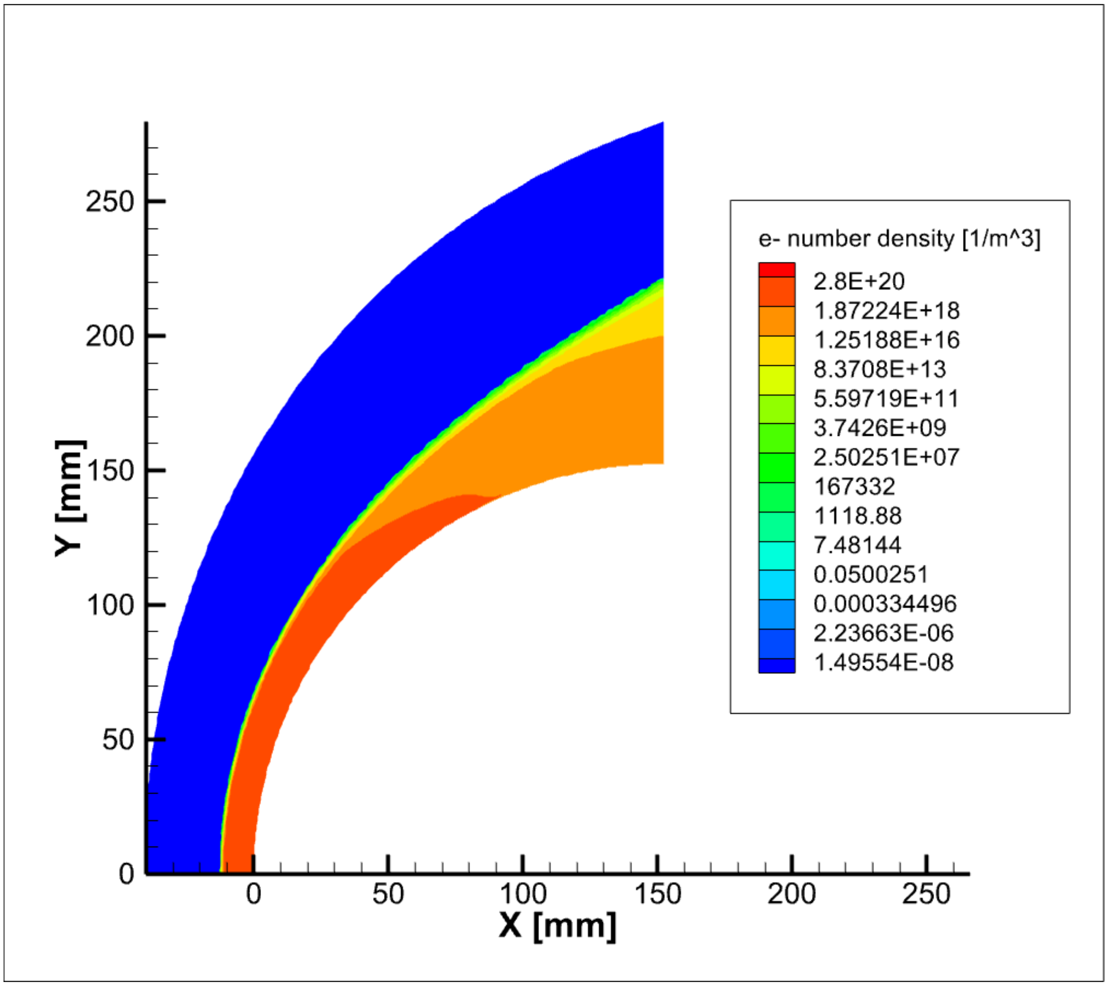

Fig. 2- Electron number density around a sphere at an altitude of 40 kilometres at a Mach number of 15.

Moreover, plasma frequencies in the flow field, as seen in Fig.3, reach extremely high values, up to two orders of magnitude higher than the reference frequency. This implies that any incident wave incident with that frequency will be evanescent downstream of the shock. In Fig.4, the collision frequency also shows interesting behaviour. Due to the sub-orbital altitude, the shock layer contains a collisional region that cannot be ignored, where the frequencies reach up to 45 GHz near the wall and 35 GHz in the normal shock zone.

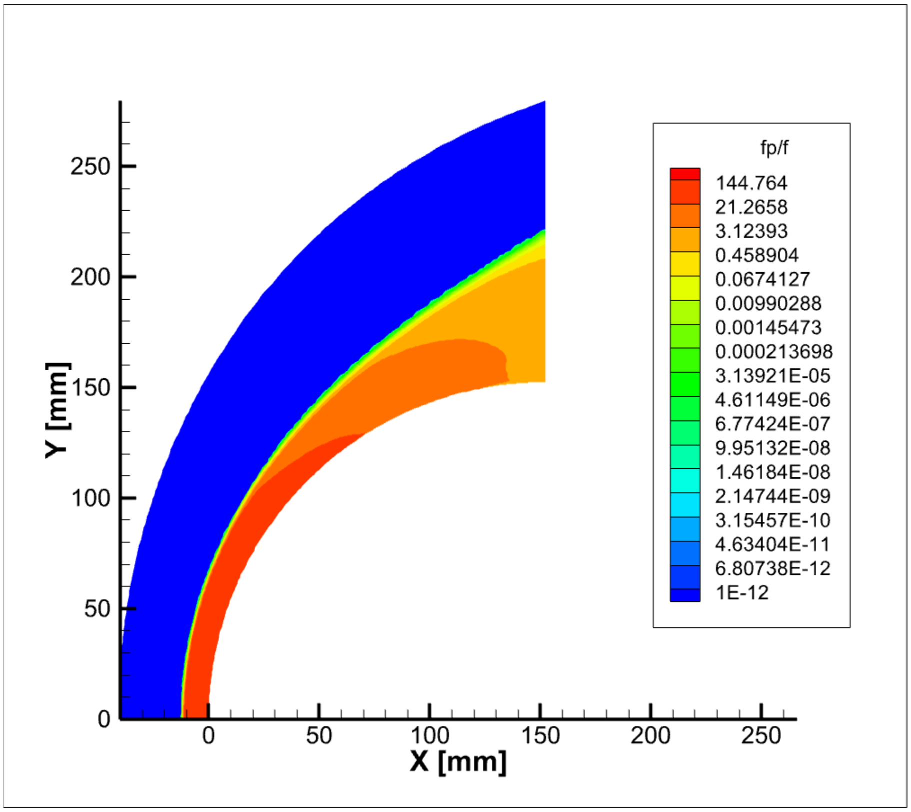

Fig. 3- Plasma Frequency around a sphere at an altitude of 40 kilometres at a Mach number of 15.

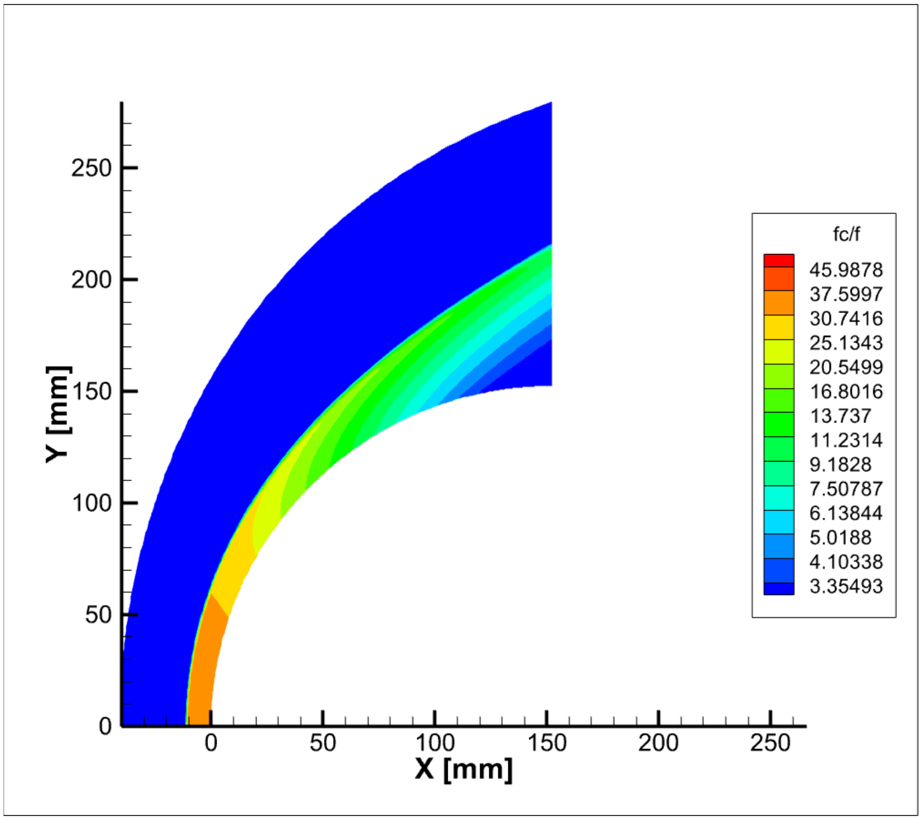

Fig. 4- Collision Frequency around a sphere at an altitude of 40 kilometres at a Mach number of 15.

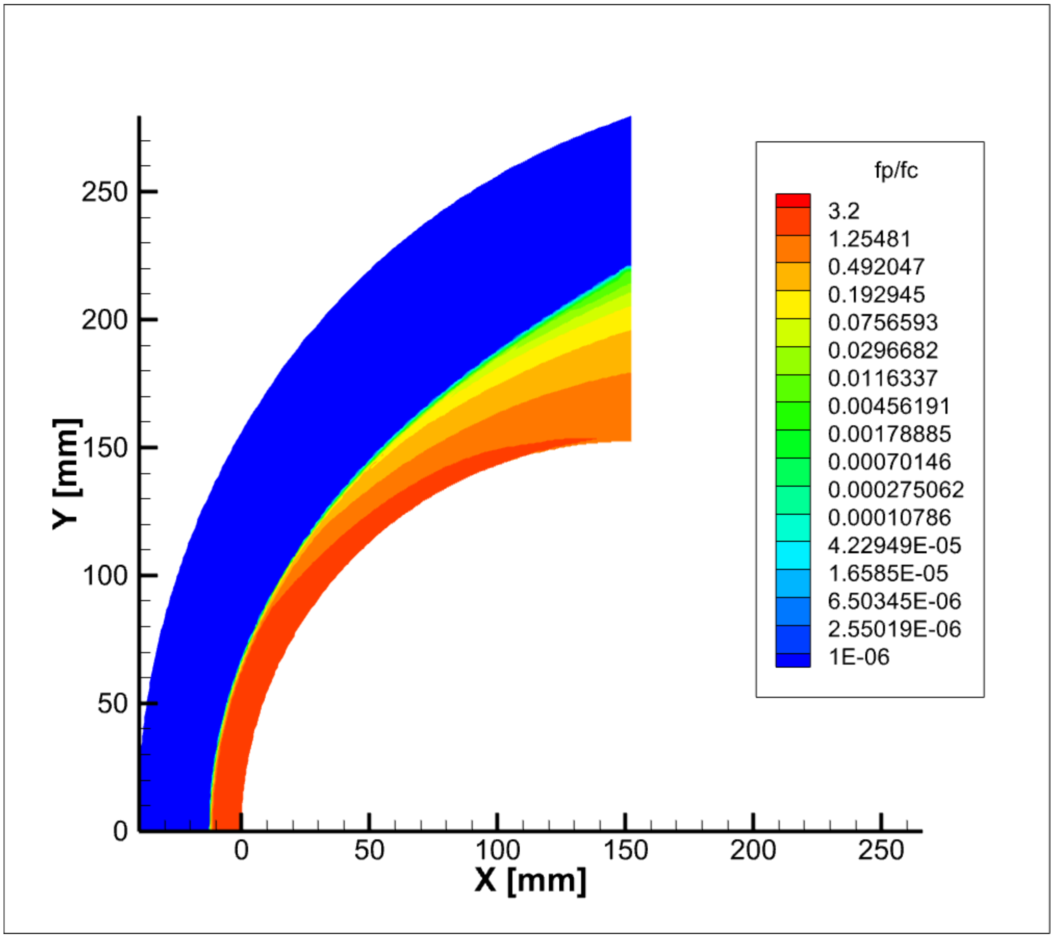

Fig. 5—Collision Frequency and Plasma Frequency ratio around a sphere at an altitude of 40 kilometres at a Mach number of 15.

Understanding the propagation of electromagnetic waves in plasma is crucially dependent on the ratio between two parameters, as illustrated in Fig.5. In the specific flight conditions examined, the results demonstrate that the propagation of electromagnetic waves is evanescent downstream of the shockwave due to the high plasma frequencies. It is worth noting that collisional absorption appears to be less dominant than the aforementioned phenomenon.

Conclusions

This study presents a numerical model for predicting plasma formation in suborbital hypersonic flight conditions. the analysis reveals that at a flight altitude of 40 kilometers and a Mach number of 15, the shockwave induces significant thermal effects downstream, resulting in a critical zone with high-temperature effects. The investigation shows that the plasma and collision frequencies in the flow field reach extremely high values and that the propagation of electromagnetic waves is mainly evanescent for high plasma frequencies. Moreover, collisional absorption is less preponderant than the cut-off phenomenon. Our research provides valuable insights into the behavior of plasma in hypersonic flight conditions and has the potential to aid in improving the radio communication capabilities of hypersonic vehicles.

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