Optimization of Hypersonic Re-Entry Vehicle Aerodynamics for Communication Blackout Mitigation

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***Abstract*— Re-entry space vehicles, traveling at hypersonic speeds (Mach 20 or higher), encounter communication blackout due to plasma sheath formation. The extreme heat from air compression ionizes molecules, increasing electromagnetic wave absorption and reflection. To mitigate this effect, various techniques such as aerodynamic shaping, magnetic windows, and liquid injection have been explored. This study presents a multiphysics approach to investigate aerodynamic shape effects on plasma formation. In this contribution Computational Fluid Dynamics, for ionized chemical densities, and electromagnetic simulations, via the Scattering Matrix Method, are performed on geometries morphed using the Radial Basis Function method. The results are used to build a surrogate model which can be used to find the optimal shape to mitigate the blackout effect.**

***Keywords*— hypersonic, communication blackout, plasma.**

I. Introduction

Hypersonic re-entry space vehicles face a critical problem known as communication blackout. The extreme friction and compression of air in front of the vehicle, moving at hypersonic speeds, generate temperatures of several thousand degrees Celsius, causing the air molecules to ionize. As a result, a plasma sheath forms around the vehicle, increasing electromagnetic (EM) reflection and absorption of an incoming or radiating wave. This effect may lead to a communication blackout of electronic devices located on the vehicle [1]. Several approaches have been developed to mitigate the effect of communication blackout, such as aerodynamic shaping, the magnetic window, and liquid injection [2]. Aerodynamic shaping for the blackout mitigation in hypersonic vehicles represents a really challenging topic since full-wave EM simulation of aerodynamic shape modification may be impractical in many cases, due to object physical dimensions larger than wavelength. However, numerical simulations of blackout mitigation techniques are an important tool during the vehicle design phase.

In this paper, a multiphysics approach for the investigation of the effect of the aerodynamic shape in the plasma sheath formation is proposed, as shown in Fig. 1. The process initiates with Computational Fluid Dynamics (CFD) calculations of ionized chemical densities, employing models such as those proposed by Gupta et al. [3]. These densities are subsequently utilized to determine the EM complex conductivity of the plasma [4]. The EM complex conductivity data serve as inputs for simulations using the Scattering Matrix Method

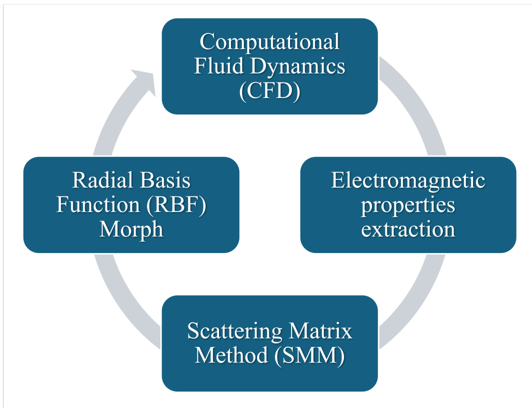

Fig. 1. Main steps of the multiphysics workflow for the shape optimization of the hypersonic vehicle.

(SMM), enabling the analysis of communication blackout effects [5]. Finally, the application of Radial Basis Function (RBF) mesh morphing techniques allows for the adaptation of computational grids, providing the flexibility to modify geometrical configurations efficiently. This adaptability is crucial for conducting comprehensive Design of Experiments (DOE), as it permits systematic exploration of design variations and their impacts on simulation outcomes.

II. Methodology

In optimization theory, a DOE is a systematic process in which input variables are adjusted following specific rules to observe their effects on the output. This iterative approach is used to collect response data, especially when multiple inputs are involved. By simultaneously varying several inputs, DOE can identify significant interactions between them. To perform a DOE, it is necessary to define the problem and select the variables, known as *factors*. Then a design space (*region of interest*), which specifies the range of possible values (*levels*) for each factor, must be established and sampled [6]. Several sampling techniques exist; in this work a Full Factorial Design (FF) is chosen since the number of variables and their levels is limited. This design examines all possible combinations of the variables, ensuring that the effect of each parameter is isolated. Consequently, it facilitates a clear evaluation of the interactions among the variables.

CFD for hypersonic simulations involves the solution of compressible Navier-Stokes equations, which govern mass, momentum, and energy conservation in high-speed flows [7]. The Knudsen number (Kn) determines whether the flow is in the continuum or rarefied regime, with Kn < 0.1 indicating a continuum regime where the classical dynamics of fluids applies. In this regime, the equations account for viscous and thermal diffusion, which is essential to model temperature gradients and shock interactions [8]. The two-temperature model for hypersonic flows describes the thermodynamic behavior of a gas using two distinct temperatures: the translational temperature, which represents the temperature of gas particles due to their bulk motion, and the vibrational temperature, which accounts for the energy associated with the internal vibration modes of molecules [9].

The generated temperature distribution $T(x, y, z)$ and the chemical species volumetric concentrations are used to calculate the the plasma frequency ω_p and the electron collision frequency ν_c, as in [4],

$$\omega_p = \sqrt{\frac{e^2 n_e}{\varepsilon_0 m_e}} \tag{1}$$

$$\nu_c = 6.3 \times 10^{-15} n_m \sqrt{\frac{T}{300}} \tag{2}$$

where $n_e(x, y, z)$ is the concentration of electrons and $n_m(x, y, z)$ the concentration of all the other species. From these parameters, it is possible to characterize the plasma surrounding the vehicle and to extract the complex conductivity from (3).

$$\sigma = \frac{\omega_p^2 \varepsilon_0 \tau}{1 + j\omega\tau} \tag{3}$$

where τ is the relaxation time of electrons, defined as the reciprocal of the collision frequency. The EM interaction with the plasma is simulated using a SMM [5] and the space-varying properties are modeled as a multilayer material with constant conductivity and finite thickness. From the simulation, it is possible to obtain the reflection, absorption, and transmission coefficients, and thus the frequency at which the communication blackout occurs.

A. Numerical Approach for hypersonic simulations in Ansys Fluent

The settings described for hypersonic CFD simulations in ANSYS Fluent are tailored to address the complex phenomena associated with high-temperature, compressible, and reactive flows. First, the two-temperature model is enabled to capture partial ionization effects at temperatures exceeding 10.000 K. A mixture of eleven air species (nominally O, O^+, O_2, O_2^+, N, N^+, N_2, N_2^+, NO, NO^+ and e^-) based on Gupta's model is used [3], and volumetric reactions are enabled to accurately simulate chemical processes. Specific heat is modeled using the Boltzmann-Kinetic theory, while viscosity and thermal conductivity are derived from the Kinetic theory, both of which are essential for high temperature flows [10].

The density-based solver with an implicit formulation is used, providing stability and efficiency in handling compressible flows, which is particularly important for hypersonic conditions. High-Speed Numerics are enabled to further optimize the handling of compressibility effects, while the Green-Gauss Cell-Based method with Roe's scheme is chosen for gradient evaluation to ensure accurate shock-capturing in the flow. To enhance the resolution of boundary layers, Enhanced Convergence Acceleration for Stretched Meshes (CASM) is employed. This improves convergence rates in simulations where fine mesh resolution is required near walls. Solution limits are carefully verified to avoid clipping of extreme pressure and temperature values that can arise in hypersonic simulations. For reacting flows, the Direct Source chemistry solver is selected, which is suitable for accurately modeling chemical reactions in high-temperature flows. Convergence stabilization is achieved by reducing the Courant–Friedrichs–Lewy (CFL) number to 1 and lowering the positivity rate limit to 0.05, ensuring that the solution remains physically realistic. High-order term relaxation is enabled for all variables, and the solver begins with first-order schemes to accelerate convergence, transitioning to second-order discretization once the flow is fully developed. Finally, Full Multigrid (FMG) initialization is used after standard initialization to improve the robustness of the initial solution. FMG settings are adjusted for small cases by reducing the number of levels in the coarse grid and lowering the CFL value to 0.25 for improved stability. Viscous FMG is enabled to account for boundary layers and heat transfer, while Species-Reaction FMG is used for accurate initialization of reactive flows.

III. Numerical Validation

As a numerical validation, the workflow is applied to a cylindrical geometry oriented in the z-axis. The CFD is set to simulate a vehicle moving at Mach 20, as shown in Fig. 2a. The temperature distribution for the base geometry is plotted in Fig. 2b. The EM propagation in the plasma is simulated with the SMM from the temperature and the densities of chemical species. In particular, in the stagnation line (see Fig. 2a, the obtained reflection, absorption, and transmission coefficients are plotted in Fig. 3. A cutoff frequency is defined at which the plasma sheath starts to reflect the signal and leads to a communication blackout. This frequency represents a Quantity of Interest (QOI), which can be used for a design space exploration. For the DOE, two orthogonal points are chosen. The first is located on the stagnation point of the cylinder, and the second 90° from it, as shown in Fig. 2a. The two points, and consequently the computational mesh, are morphed with an RBF method. The levels of the sampling points and the measured QOI are presented in Table 1. The electron concentration in the nine morphed configurations is depicted in Fig. 4.

The sampled points from the design space, obtained via a full-factorial exploration, are used to construct a Response Surface (RS) that approximates the response variables across that space. The RS acts as a surrogate model to estimate the set of input parameters that yield an optimal response. Once an

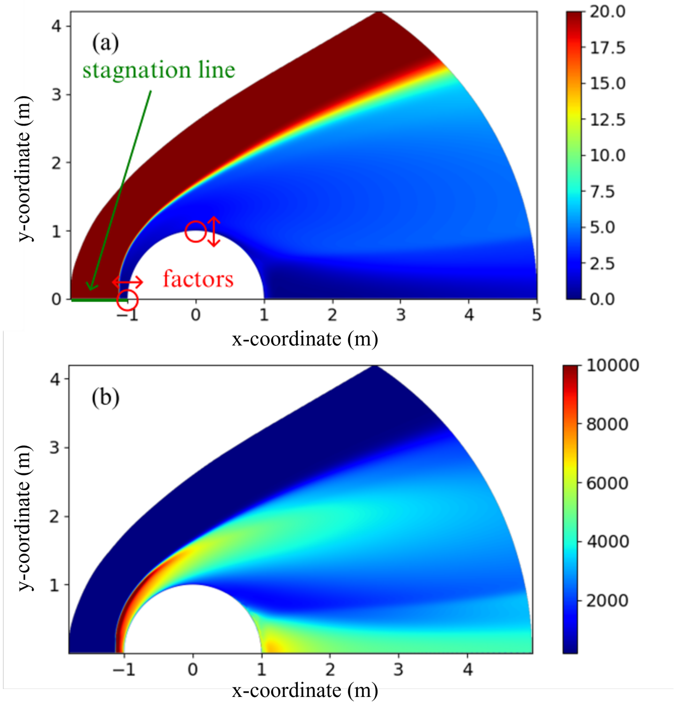

Fig. 2. (a) Mach number and (b) temperature distribution in Kelvin of the basic configuration. The control variables (factors) are highlighted in red and the arrows show their degree of freedom; in green it is shown the stagnation line where the QOI (electrons density) is measured.

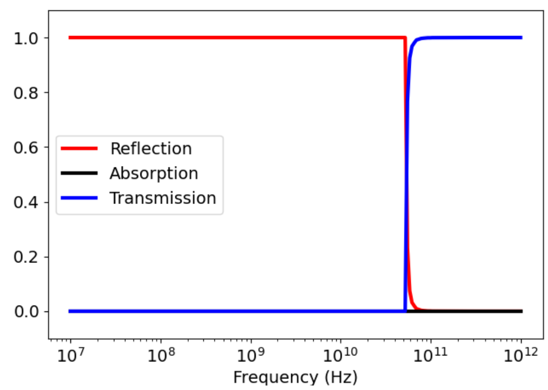

Fig. 3. Reflection, absorption and transmission coefficient for a plane wave propagating in the stagnation line.

optimal solution is identified using this model, it is validated against the actual physics of the problem. The surrogate model can be built by choosing among a wide range of techniques; in the present work the construction of the surrogate model is based on the Kriging method [11], belonging to the family of linear least squares algorithms. The estimation of the response variable at a point $\mathbf{x}$ is given by a linear combination of the DOE results, such as:

$$\hat{f}(\mathbf{x}) = \sum_{i=1}^{N} \lambda_i(\mathbf{x}) f(\mathbf{x}_i) = \sum_{i=1}^{N} \lambda_i(\mathbf{x}) y_i \tag{4}$$

Table 1. Summary of the DOE sampling. The factors x and y represent the distance from the base position. The QOI is frequency at which communication blackout happens in the stagnation line.

x (m)	y (m)	QOI (HZ)
0.00	0.00	4.94e10
0.00	0.05	4.15e10
0.00	0.10	4.40e10
-0.05	0.00	1.96e10
-0.05	0.05	6.99e10
-0.05	0.10	2.61e10
-0.10	0.00	2.77e10
-0.10	0.05	2.61e10
-0.10	0.10	2.93e10

where $\mathbf{x}$ is the vector of the k input parameters, $\hat{f}(\mathbf{x})$ is the output of the interpolated function and λ_i are the weights of the interpolation and solution of a system of linear equations. The Kriging interpolation is included in several open libraries such as Surrogate Modeling Toolbox [12]. The surrogate model is illustrated in Fig. 5a. The blue crosses are the training points, while the green dots represent the validation ones. At this stage, the surrogate model is still rather coarse, and other training and validation points need to be added to improve the accuracy of the model and perform an optimization process.

Another QOI consists of the integral of the electron concentration in the stagnation line. This choice is related to the need to reduce the plasma sheath thickness in the communication region to apply other strategies to mitigate blackouts. A second surrogate model has been trained using this QOI, as shown in Fig. 5b. From the comparison of both figures, it can be noticed that the best configuration for the minimization of the cutoff frequency and the thickness of plasma layer are opposite. For this reason a multi-objective optimization is required to obtain the best solution.

IV. Conclusion

This study presents a multiphysics methodology to analyze the impact of aerodynamic shape on plasma sheath formation. The approach integrates CFD for modeling ionized chemical densities with the calculation of the plasma's EM complex conductivity, which is essential for simulating communication blackout effects. The study employs RBF mesh morphing techniques to adapt computational grids, enhancing the flexibility to modify geometric configurations to conduct a DOE. Moreover, at the cost of increasing computational resources, the proposed workflow can account for different dimensions and can provide a solution for various materials. The training of surrogate models from the DOE which account for all the QOI (cutoff frequency, thickness of plasma layer, aerodynamic performances, etc...) allows multi-objective and multiphysics optimization of the aerodynamic shape of a re-entry vehicle, helping in mitigating the effect of communication blackout.

References

[1] E. David, M. Jeffrey, S Jamey, *et al.*, "Radio frequency (rf) blackout during hypersonic reentry," *AIAA. 13th International Space Planes and Hypersonic Systems and Technologies. Capua, Italy: AIAA*, 2005.

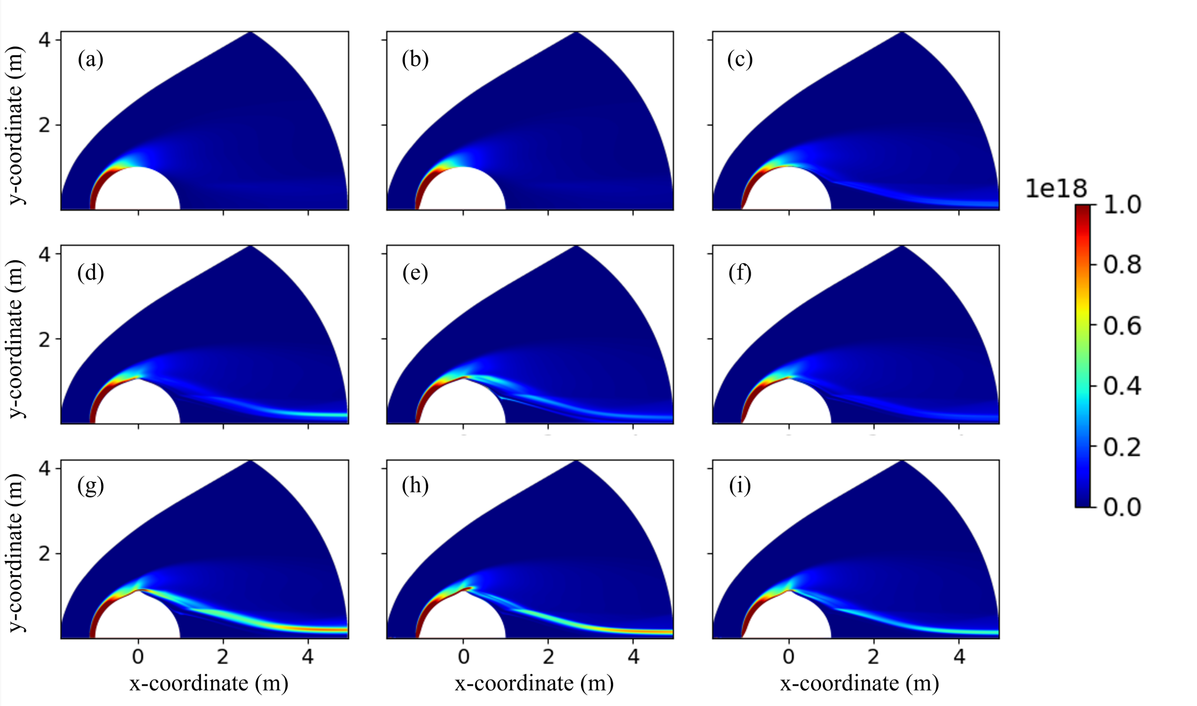

Fig. 4. Electron concentration in m^{-3} for all the nine morphed geometries studied in the design of experiment.

[2] E. D. Gillman, J. E. Foster, and I. M. Blankson, "Review of leading approaches for mitigating hypersonic vehicle communications blackout and a method of ceramic particulate injection via cathode spot arcs for blackout mitigation," NASA, Tech. Rep., 2010.

[3] R. N. Gupta, J. M. Yos, R. A. Thompson, and K.-P. Lee, "A review of reaction rates and thermodynamic and transport properties for an 11-species air model for chemical and thermal nonequilibrium calculations to 30000 k," NASA, Tech. Rep., 1990.

[4] Z. Yuan and J. Shi, "Electron collision frequency of the non-magnetized plasma," *Nuclear Fusion and Plasma Physics*, vol. 24, no. 2, pp. 157–160, 2004.

[5] B. J. Hu, G. Wei, and S. L. Lai, "Smm analysis of reflection, absorption, and transmission from nonuniform magnetized plasma slab," *IEEE transactions on plasma science*, vol. 27, no. 4, pp. 1131–1136, 1999.

[6] M. Cavazzuti, *Optimization methods: from theory to design*. Jan. 2013, ISBN: 9783642311864.

[7] V. Casseau, R. C. Palharini, T. J. Scanlon, and R. E. Brown, "A two-temperature open-source cfd model for hypersonic reacting flows, part one: Zero-dimensional analysis," *Aerospace*, vol. 3, no. 4, p. 34, 2016.

[8] J. D. Anderson, *Hypersonic and high temperature gas dynamics*. AIAA, 1989.

[9] I. Nompelis, G. V. Candler, and M. S. Holden, "Effect of vibrational nonequilibrium on hypersonic double-cone experiments," *AIAA journal*, vol. 41, no. 11, pp. 2162–2169, 2003.

[10] E Zoby, A Simmonds, and R Gupta, "Temperature-dependent reaction-rate expression for oxygen recombination at shuttle entry conditions," in *22nd Aerospace Sciences Meeting*, 1984, p. 224.

[11] G. Matheron and F. Blondel, *Traité de géostatistique appliquée* (Mémoires du BRGM v. 1). Editions Technip, 1962. [Online]. Available: https://books.google.it/books?id=TDl0jgEACAAJ.

[12] P. Saves, R. Lafage, N. Bartoli, *et al.*, "SMT 2.0: A surrogate modeling toolbox with a focus on hierarchical and mixed variables gaussian processes," *Advances in Engineering Sofware*, vol. 188, p. 103 571, 2024. DOI: https://doi.org/10.1016/j.advengsoft.2023.103571.

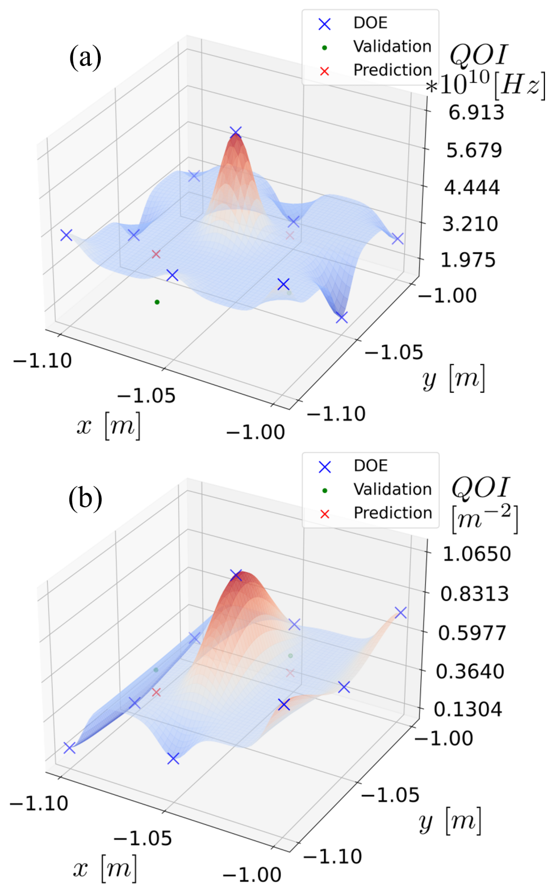

Fig. 5. Surrogate model, obtained through Kriging interpolation, of (a) the cut-off frequencies and (b) the integral of the electron density. The blue crosses represent the training points, the green dots are the validation ones obtained with simulation, and the red crosses the predicted points for the same factors and levels.