



COB-2021-1172

THERMOCHEMICAL NONEQUILIBRIUM COMPUTATION OF APOLLO CAPSULE DURING THE REENTRY PHASE

Fortunato Martins Neto

Instituto Tecnológico de Aeronáutica, São José dos Campos, Brazil
fortunato@ita.br

Ruan Ramon Penha dos Passos Pereira

Instituto de Aeronáutica e Espaço, Department of Aerospace Science and Technology, São José dos Campos, Brazil
passos.ruan@gmail.com

Rodrigo Cassineli Palharini

Universidad Técnica Federico Santa María, Department of Mechanical Engineering, Santiago, Chile
rodrigo.cassineli@usm.cl

Cayo Prado Fernandes Francisco

Instituto de Aeronáutica e Espaço, Department of Aerospace Science and Technology, São José dos Campos, Brazil
cayo.francisco@gmail.com

Abstract. Atmospheric reentry is the most critical part of space missions as heat protection, vehicle integrity and communications are severely affected by the extreme nonequilibrium flow conditions involving high temperatures, strong shock waves, chemical dissociation and recombination and plasma formation. The accurate prediction of these phenomena is crucial to guarantee personal and payload safety during this mission stage. The most well known method used to obtain aerothermodynamic predictions for these nonequilibrium, rarefied, chemically reacting flows is the Direct Simulation Monte Carlo (DSMC) particle method. Here, the aerothermodynamic properties around the Apollo vehicle with Mach 32 reentry conditions were analyzed, with emphasis on the quantification of the effect of nonequilibrium chemical reactions in the prediction of heat fluxes. Computations used a recent axisymmetric version of the DSMC code, *dsmcFoamPlus*, implemented in the *OpenFoam* framework. The axisymmetric model produced similar results compared to the three-dimensional model, where the inclusion chemical reactions lead, as expected, to endothermic effects decreasing heat fluxes on the vehicle surface. Furthermore, the axisymmetric results shows the advantages, at least in the preliminary design phases, of the much less computationally demanding axisymmetric DSMC code.

Keywords: DSMC, Reentry, Apollo Vehicle, Aerothermodynamics, Chemical Reactions

1. INTRODUCTION

In recent years, a trend has been observed towards greater reuse of space vehicles. For example, the north-american company SpaceX recently developed the partially reusable launch vehicle Falcon 9, whose first stage is able to land vertically after separation from the second stage. The reuse of vehicle higher stages, however, requires a series of engineering studies to ensure the vehicle safety during its reentry into the Earth's atmosphere and/or other planetary atmospheres such as recently happened with Perseverance's Rover in Mars atmosphere.

During the reentry phase, the vehicle is subjected to extremely unfavorable aerothermodynamic conditions, being exposed to high values of temperature and pressure. In this sense, it is important to carry out fluid mechanics studies to assess these aerothermodynamic properties, which are important to supply the thermal protection project and also the stability and control predictions of the spacecraft.

Under reentry initial conditions the atmosphere is rarefied, such that atmospheric properties are very different from those observed at sea level. Hence, the Navier-Stokes equations usually employed to calculate the fluid dynamics are not adequate to model this condition, because the continuous hypothesis is no longer valid and the results obtained are quite imprecise ((Moss *et al.*, 2006)). In this context Bird (1994) pioneeringly proposed the DSMC¹ method, a stochastic particle approach, loosely based on the Boltzmann equation, to solve the kinetic equations of motion in order to calculate the aerothermodynamic properties of the flow around space vehicles in rarefied conditions. The method was

¹Direct Simulation Monte Carlo (DSMC).

then successfully applied in different studies in the last decades, as in (Bird, 1981), (Moss *et al.*, 2006), (Palharini and Azevedo, 2015) and (White *et al.*, 2018).

A number of different space missions have undergone reentry conditions in the last decades. Some of the most well documented missions concerning hypersonic reentry aerothermodynamics are the Apollo missions, widely used in north-american space program in last century. The Apollo capsule experienced high aerothermodynamics loads acting on it surface during the reentry phase, so that accurate studies of this phase were executed, including theoretical and numerical predictions, experimental wind tunnel tests and in flight measurements demanded to guarantee that the vehicle would resist to the extreme conditions.

When reaching the reentry stage the vehicle undergoes hypersonic flow conditions, which particular characteristics must be well-evaluated. The extreme variation of thermodynamics properties across shock waves, viscous dissipation with hypersonic boundary layers and radiative heat transfer creates high temperatures that excite rotational and vibrational internal energy modes within the molecules, leading to chemical dissociation and recombination and even electronic ionization of the atoms and molecules (Jr, 2003).

High temperature chemically reacting flows have influence in the aerodynamic parameters of the vehicle, as chemical reactions occurring during the reentry phase are mainly endothermic, and being the high heat transfer rates to the surface the most dominant aspect in high temperature hypersonic flows Jr (2003). Allen and Eggers (1958) showed that an efficient reentry vehicle shape profile should be subject to a low heat flux and high drag to dissipate the enormous amount of kinetic energy.

The present work presents a numerical aerothermodynamics analysis of Apollo capsule in reentry conditions using two DSMC approaches: axisymmetric and 3D². The axisymmetric configuration is usually employed in computational analysis due to its advantage regarding the computational costs needed to achieve a solution to the flow conditions. These results were used in comparison to the three-dimensional ones in order to analyze both the numerical flow predictions of the main aspects of aerothermodynamics properties and the numerical costs and feasibility of the axisymmetric DSMC.

The numerical computations employed the OpenFOAM framework to perform the aerothermodynamic analysis of the rarefied hypersonic flow conditions over the Apollo through the *dsmcFoamPlus* solver and its recently axisymmetric implementation by (White *et al.*, 2018).

2. COMPUTATIONAL METHOD

In this section the DSMC method used to perform the thermochemical nonequilibrium flow analysis is presented.

2.1 DSMC METHOD

The DSMC method, as presented by Bird (1994), is a stochastic particle method based on the Kinetic Theory assumptions. The DSMC perform an approximation which consists in decoupling the molecular dynamics in advective noninteracting motions and intermolecular collisions into two successive stages at a time step Δt , proportional to the MCT³ between molecules, so that the particles movement is modeled deterministically, while collisions are treated statistically.

As the DSMC operates in the kinetic scales, to represent the huge number of particles (atoms and molecules) presented in real flows the method utilizes virtual (or equivalent) particles that represent a large number of real particles, as an approximation of the real number of molecules in real flow conditions. For this to be accomplished there are some restrictions on the minimum number of molecules used in computational cells. In this context, as the collision rate is a function of the number of molecules, it is desired that there are as many molecules as possible. Furthermore, a suitable time step must be chosen in order to capture the particle collision dynamics. Thus, the time step should be sufficiently smaller than the mean collision time and the cell size Δx , used to perform near neighbor collisions and sampling the flow properties, must be smaller than the mean free path λ_∞ of gas molecules. The mean free path can be defined as

$$\lambda_\infty = Kn \frac{\phi}{\nabla\phi}, \quad (1)$$

where Kn is the Knudsen number, used to evaluate the degree of rarefaction of the gas; and $\frac{\phi}{\nabla\phi} = l$, where l is the flow characteristic length, taken as the diameter of a reentry capsule or defined by the gradient of any macroscopic property (as shown in the equation above).

²Three-dimensional (3D).

³Mean collision time (MCT)

Palharini (2014) suggests that for a good compromise between physical accuracy and computational efficiency of the DSMC method, the cell size must be stipulated as close as possible from

$$\Delta x = \frac{\lambda_{\infty}}{3} \quad (2)$$

to obtain accurate results from simulations in a reasonable computational time. In addition two more parameters are crucial when performing DSMC computations, namely, the number density n_{∞} which is a measure of the number of particles per unity volume and the equivalent number of particles nEP that stipulates the relation between the simulation, virtual, particles and the number of real particles in the flow.

After the particles are advected and collided their properties are sampled and the time-averages of these properties are used to calculate the macroscopic gas parameters (Bird, 1994). Thus, the DSMC method is capable of calculating nonequilibrium flow properties in rarefied conditions, resolving the physical characteristics of hypersonic reentry.

The DSMC model used for the current simulations is the *dsmcFoamPlus* (White *et al.*, 2018) solver algorithm, designed within the OpenFoam (Foundation, 2021) framework. It consists of a fully parallel numerical implementation that allows the particles initialization, tracking and admits the simulation of permanent and transient conditions.

3. CHEMISTRY MODELING

For a long time studies of chemically reacting gas flows using the DSMC method have employed procedures that were first introduced by (Bird, 1979) through the called TCE⁴ model. In these studies, equilibrium kinetic theory was used to convert the rate coefficients that are defined in terms of the macroscopic gas temperature to collision probabilities that are functions of the energy of the collision. In essence, the model relies on the availability of reliable data for the reaction rates, so to overcome this limitation, efforts have been made to develop a model that makes no use of existing rate equations the Q-K model.

Bird (2011) describes a chemical reaction model called Q-K⁵ which uses a 5-species air-model based on microscopic gas considerations. The molecular species of nitrogen (N₂), oxygen (O₂), nitric oxide (NO), nitrogen (N) and oxygen (O) atoms are considered and four different reaction types can be defined, two types of dissociation, molecular recombination and exchange reactions. In the simulation of high temperature rarefied flows, the chemical processes are described by 19 individual reactions, where the recombination is neglected. Bird (2011) points that the probability of a recombination in a binary collision is equal to the probability of a third molecule being within a “ternary collision volume”. This probability is very low because the λ_{∞} at high altitudes is comparable to the reentry capsule size, and therefore can be neglected. In addition, this reaction type can become important in low-altitude simulations where “high density” values are found.

In this model, the Q-K condition for dissociation and recombination phenomena is that the energy in a collision should be high enough to permit the excitation of the vibrational mode corresponding to molecular dissociation energies, modeling the energy exchange between the vibrational and electronic modes to the translational energy mode. The vibrational energy mode is part of the total energy and limits the amount of post-collision energy available to the translational and rotational energy modes.

As an expansion of the quantum-kinetic scheme, Lietchy and Lewis (2011) proposed a Q-K model including reactions involving charged species. In the present work, this 11 species reactions model (N₂, O₂, NO, O, N, N₂⁺, O₂⁺, NO⁺, O⁺, N⁺, e⁻) was employed into the *dsmcFoamPlus*. The advantages consist of a more accurate prediction of the flowfield structure around the vehicle, surface properties and shock wave structure.

3.1 CAPSULE GEOMETRY AND FREESTREAM CONDITIONS

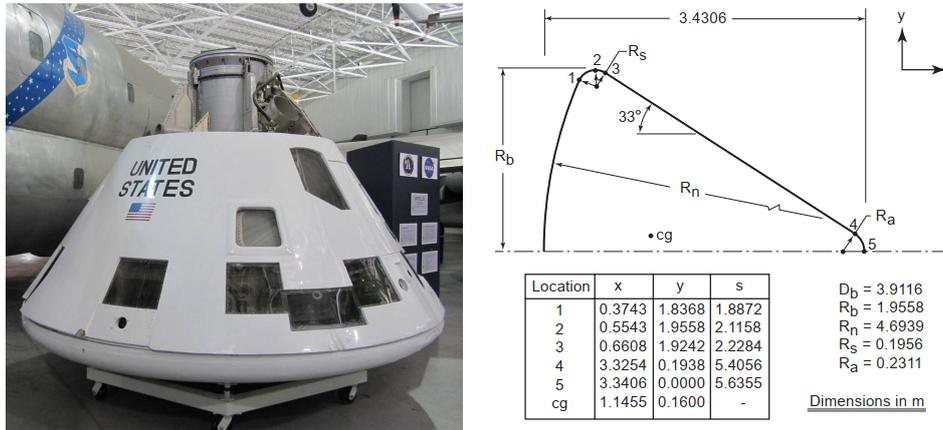
The Apollo capsule was extensively used by NASA⁶ in last century and is worldwide known as a command module that transported the first human-beings to the Moon in the 1969 Apollo 11 Mission. The dimensions used in this work are based in the data provided by (Moss *et al.*, 2006). The Apollo has a length of 3.4306m and a diameter D_b of 3.9116m. Figure 1 a) shows a real Apollo picture and 1 b) its dimensions.

The DSMC simulations were performed both in an axisymmetric and 3D models. In these cases a 0° angle of attack was implemented, hence the freestream is parallel to the X-axis.

⁴Total collision energy (TCE).

⁵Quantum Kinetic (Q-K).

⁶National Aeronautics and Space Agency (NASA).



(a) Apollo Capsule. (b) Apollo dimensions (Moss *et al.*, 2006).
 Figure 1. Apollo capsule.

The freestream properties were also based in conditions provided by (Moss *et al.*, 2006), where the Apollo capsule is simulated for hypersonic rarefied reentry conditions.

The conditions applied corresponds to a reentry phase at 105 km altitude. The flow conditions in Table 1 were used to perform chemical reactions computations. In 105 km altitude the atmosphere composition is characterized by N_2 78,319%, O_2 15,808% and O 0,587%. The freestream mean free path was determined using the VHS⁷ molecular model (Bird, 1981). The Knudsen number defined as the ratio of the molecular mean free path to a characteristic dimension. As the Knudsen number was provided by Moss, the mean free path was obtained using the capsule diameter as the characteristic dimension, providing $\lambda_\infty = 0.316$. The reentry velocity employed was 9600 km/s.

Table 1. Reentry freestream conditions for the Apollo simulation at 105 km altitude..

Condition	Value
Mach	32
Velocity V_∞ [km/s]	9600
Altitude [km]	105
Temperature T_∞ [K]	208
Number density n_∞ [m^{-3}]	5.094×10^{18}
Density ρ_∞ [kg/m^3]	2.364×10^{-7}
Pressure p_∞ [Pa]	0.0144
Knudsen Number Kn_∞	0.081

3.1.1 axisymmetric model

The DSMC simulation performed using the axisymmetric formulation for the Apollo capsule is shown in Figure 2.

The axially symmetric computational mesh was created through the use of only one cell wedge of 5° in the Y-axis direction, due the fact that OpenFOAM simulations are inherently three dimensional. Additionally, an ‘‘arc-domain’’ was employed to improve the computational calculations, since the region that was removed has no influence on the flow over the capsule.

Another feature necessary for the axially symmetric model is the usage of a RWF⁸ parameter introduced by Bird (1981) as a method to balance the particle distribution into the cells, where a particle at greater radial distance represent more real particles than a particle located near the axis. This implies that along the particle trajectories some of them will be duplicated or discarded to maintain the even number of particles per cell (Bird, 1981).

⁷Larsen-Borgnakke Variable Hard Sphere (VHS).

⁸Radial Weighting Factor (RWF).

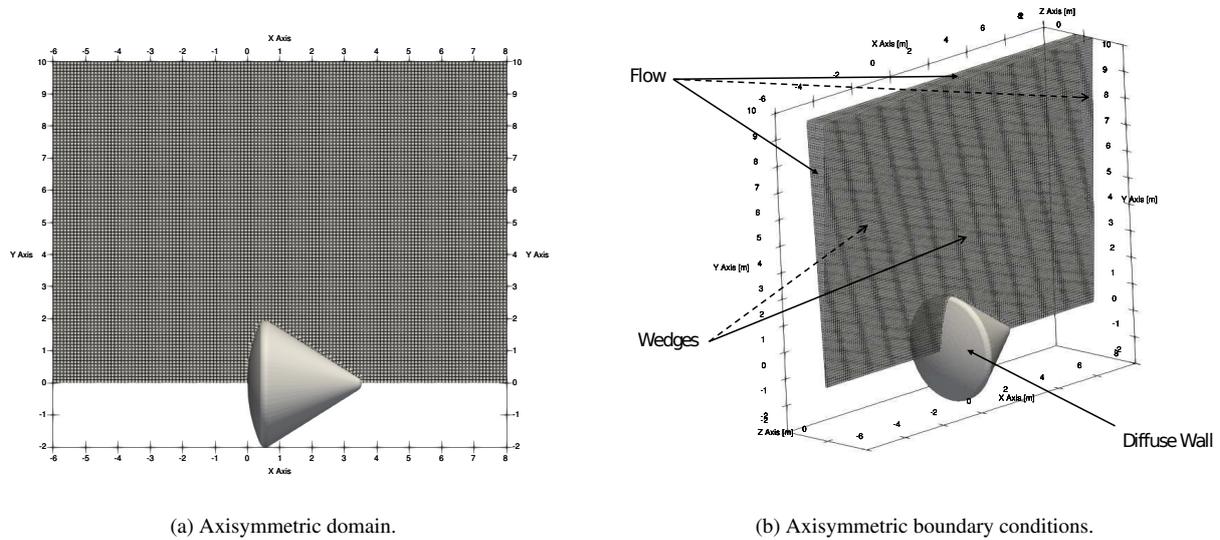


Figure 2. Apollo axisymmetric domain.

The computational mesh was initially filled with a total number of 330711 DSMC particles in a domain with 12931 cells. Symmetry boundaries conditions were applied at the “arc” region of domain, which is composed by two wedges. The inflow boundary was located 3.0 half body diameters from the capsule fore-body stagnation point and the outflow boundary was located approximately 4.0 body diameters away from the same point. The wall temperature was held constant at 1029K with the surface being modeled as a diffusive Maxwellian wall.

3.1.2 Three-dimensional model

For the three-dimensional case the computational mesh was filled with a total number of 16477310 particles in a block with 915119 cells. The same boundary conditions were applied in the capsule and boundary domains. In the the Y-axis⁹ 3.0 half body diameters distance was set. The 3D mesh details can be seen in Figure 3.

As for axisymmetric simulation and for 3D simulations there were applied a $MCT = 9 \times 10^{-4}$ and $\Delta t = 2,00 \times 10^{-6} s$.

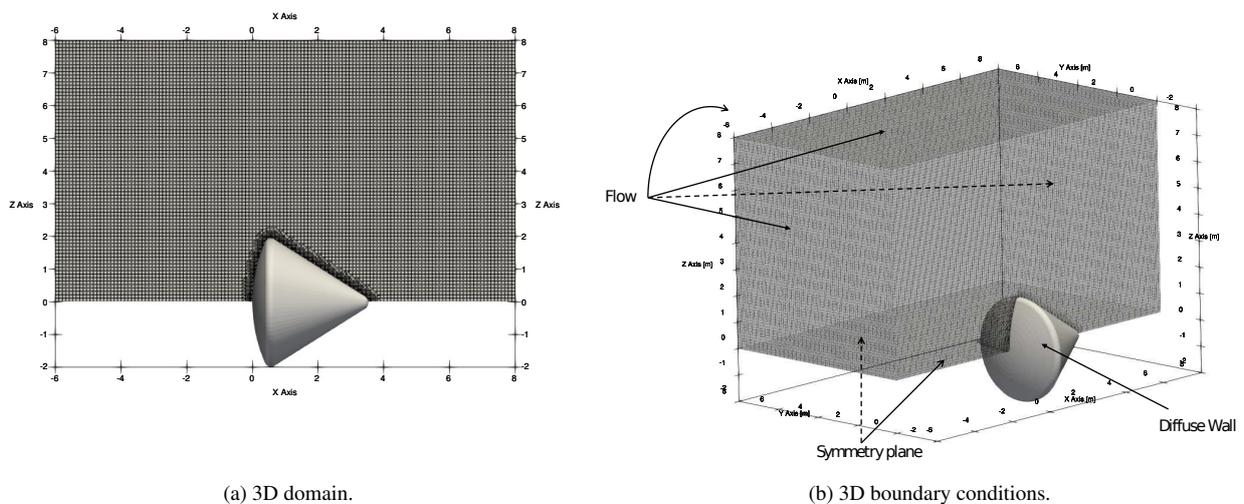


Figure 3. Apollo three-dimensional domain.

⁹There were a small difference in the axis distributions for the axisymmetric and 3D modelling. Please observe the images carefully for details.

4. RESULTS AND DISCUSSION

This section provides a discussion about the hypersonic thermochemical nonequilibrium flow calculations around Apollo capsule. In this study, two simulation models were applied, the axisymmetric and the three-dimensional one. The three-dimensional simulation was computed at the São Paulo University cluster Euler¹⁰ using 400 cores, with the solution for 100000 (one hundred thousand) iterations being achieved in 48 hours. The axisymmetric computations, otherwise, were carried on a 16 core workstation and the computations for 1000000 (one million) iterations were performed in 120 hours. In order to observe the behavior of the aerothermodynamics properties three different profiles were extracted from the domain, each of them normalized by the capsule diameter. The S_i ¹¹ represents the surface points over the capsule along the X-axis direction.

4.1 Temperature Field

In a hypersonic flow the interaction of the particles high kinetic energy with the vehicle surface converts forms a strong bow shock wave in front of the fore-body of the Apollo. Figure 4 shows the translational, rotational and vibrational temperature profiles measured from the capsule surface to the inlet boundary. The temperature values along the profiles were normalized by the freestream temperature (T_∞). In the figures, continuum lines represent the axisymmetric results, while dashed lines represent the three-dimensional results.

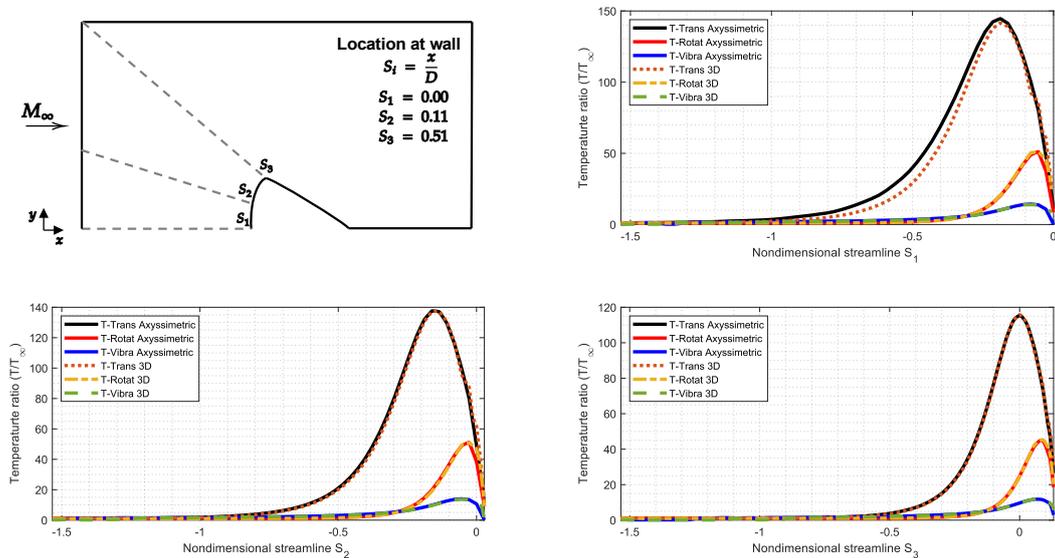


Figure 4. Temperature ratio (T/T_∞) distribution along three different profiles fore-body Apollo capsule for reacting air flow.

The profiles provided by the axisymmetric and the three-dimensional simulations presented very similar results. Small difference can be observed in the stagnation streamline S_1 in the bow shock region.

The molecules in the pre-shock region, shown by the profiles, have the same value vibrational and rotational temperatures, i.e, 0K, as almost all their energy is contained in kinetic mode. Although, along the shock region the molecules extensively strikes among themselves and their kinetic energy is redistributed to the internal modes, which is observed by the peak of rotational and vibrational temperatures shown in the figure above. Furthermore, the difference between the translational, vibrational and rotational temperature peaks demonstrates the need for the non-equilibrium simulation models.

4.2 Pressure Field

Figure 5 shows the pressure profiles, also measured from the capsule surface to the inlet boundary condition. The pressure along the profiles were normalized by the freestream pressure (p_∞).

For the pressure field good agreement was achieved by the simulation results for the axisymmetric and three-dimensional models.

An increase in the pressure field can be observed in the starting point of the bow shock ahead of the fore-body of the

¹⁰Supercomputer of Centro de Ciências Matemáticas aplicadas à Indústria (CeMAI) or in english Center for Mathematical Sciences Applied to Industry.

¹¹($S_i = x/D$) is a surface point and the corresponded streamline.

capsule and remains growing until the surface of the capsules, due the diffusive nature of of the shock in this rarefied condition.

Furthermore, as the temperature, the nondimensional profiles shows a reduction of the pressure peaks as long flow moves downstream along the body surface. For stream profile S_3 a drop pressure can be seen in the corner capsule region due to the flow expansion in the wake region.

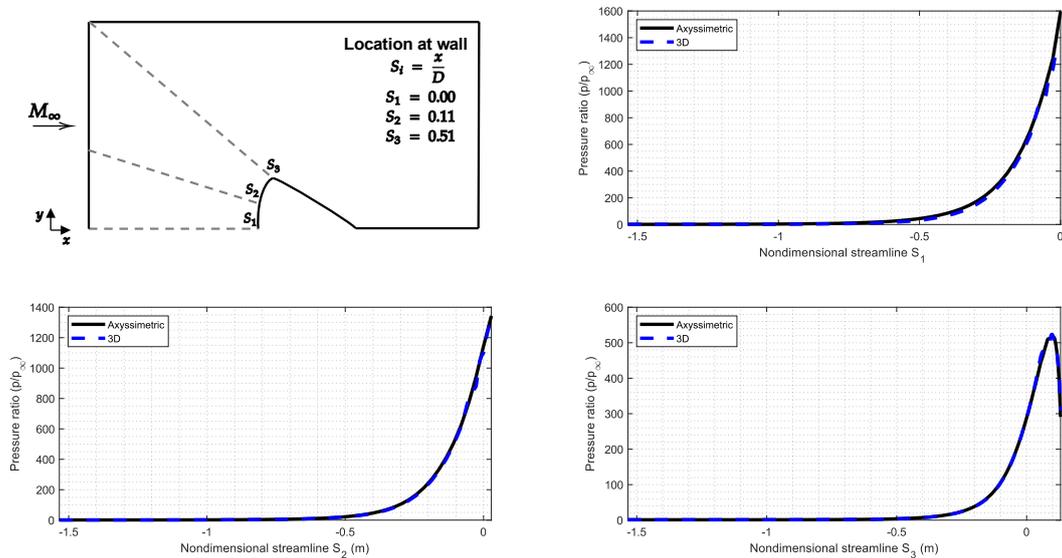


Figure 5. Pressure ratio (p/p_∞) distribution along three different profiles fore-body Apollo capsule for reacting air flow.

4.3 Density Field

Chemical reactions possess an important influence on the reduction of flow temperature around space vehicles in reentry phase. The reduction of the overall temperature is mainly caused by endothermic reactions which absorbs heat and cools the surroundings. In this process, part of the flow energy is absorbed by the gas molecules and used in dissociation process. The dissociated molecules generate new species, for example atomic oxygen. The dissociation process leads to a significant change on the flow composition around the spacecraft, as shown, for example, by Palharini and Azevedo (2015) that studied the effect of chemical reactions during reentry of the SARA brazilian reentry capsule showing important differences in the temperature and density fields.

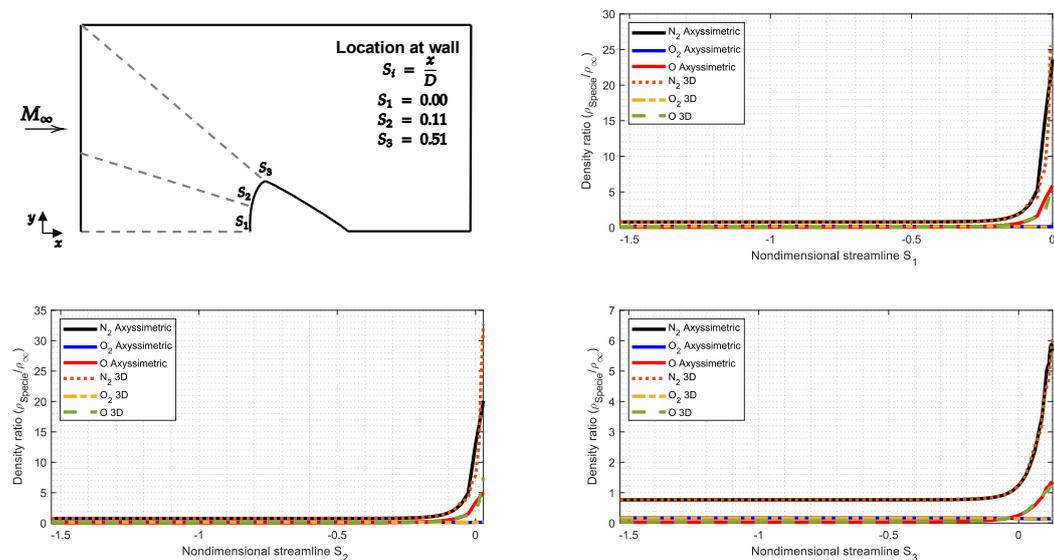


Figure 6. Density ratio ($\rho_{species}/\rho_\infty$) distribution along three different profiles fore-body Apollo capsule for reacting air flow.

The relative density profiles for N_2 , O_2 and O species are shown in Figure 6, also measured from the capsule surface

to the inlet boundary condition. The density of each specie along the profiles were normalized by the overall freestream density (ρ_∞).

The normalized density results also show good agreement between axisymmetric and three-dimensional simulations with the major differences being noted in the streamlines S_1 and S_2 near the capsule surface for N_2 density ratio, where axisymmetric results are strongly affected by the particle density in the cells.

Due to high temperatures in the flowfield over the fore-body of the capsule, dissociation reactions leads to considerable increase of atomic oxygen ratio and a consequent decrease of the O_2 . In this context, a relevant increment of N_2 density ratio close to the capsule surface can be noted.

4.4 Velocity Field

The velocity profiles are shown in Figure 7, also measured from the capsule surface to the inlet boundary condition. The velocity along the profiles were normalized by the freestream velocity (V_∞).

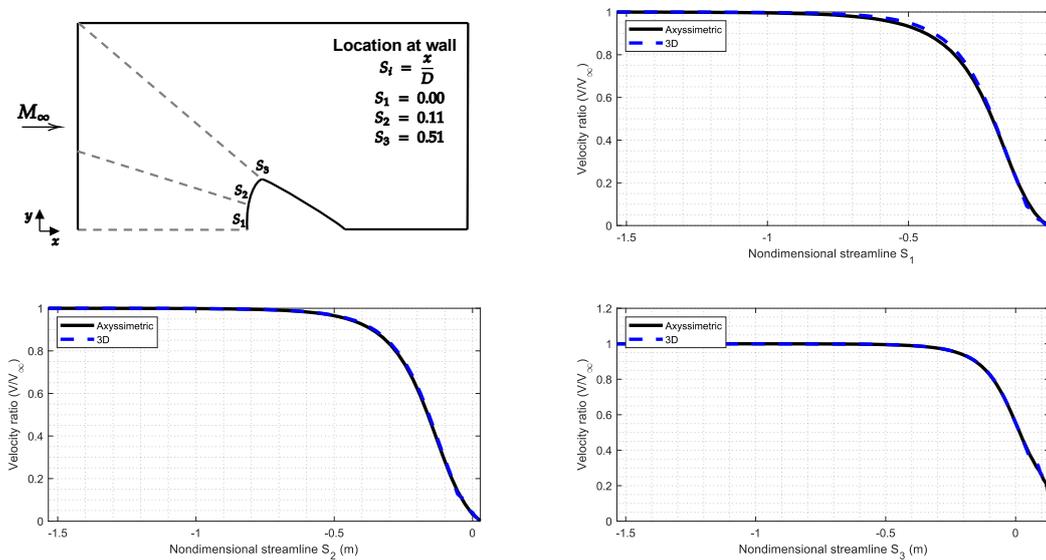


Figure 7. Velocity ratio (V/V_∞) distribution along three different profiles fore-body Apollo capsule for reacting air flow.

Velocity profile calculated by axisymmetric and three-dimensional models also had good correspondence. The velocity fore-body capsule region remains constant since the inlet boundary until the bow shock wave start point, where it decreases until zero in the capsule surface. But in surface point S_3 it's doesn't null due a tangent velocity component in the corner. Again major difference are observed for S_1 profile due to the axisymmetric cells topology.

4.5 Heat Flux Coefficient

The high Mach number flow around the Apollo capsule is dominated by high temperatures associated to thermochemical phenomena like molecular dissociation. These effects can significantly alter the heat flux over the vehicle surface. So, an accurate calculation of the heat flux C'_h over the Apollo surface is essential for the TPS¹² design which protects the internal instruments from the adverse environment thermodynamic conditions.

The stagnation streamline over the Apollo capsule is used to obtain the heat flux over the vehicle surface, Figure 8. The length along the vehicle were normalized by the Apollo length L_{Apollo} . The capsule length is measured from the stagnation point $x = 0m$ until "cone top". The surface heat difference between the simulations are more clearly observed, as the axisymmetric results are noisy when compared to 3D results, although the overall heat flux behavior shows good agreement between the simulations.

¹²Thermal Protection System (TPS).

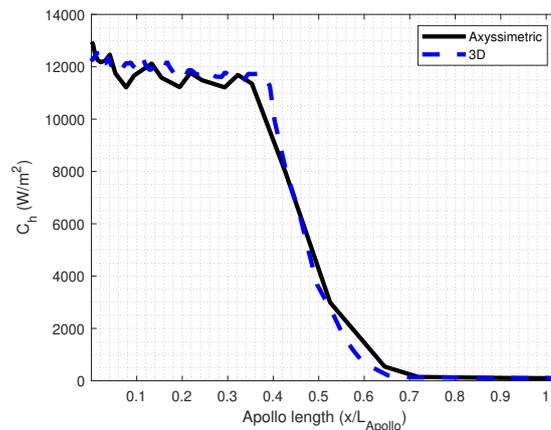


Figure 8. Heat Flux distribution along Apollo capsule length.

The data oscillation observed in both simulation models of the heat flux along the blunt body region of the capsule suggests that more computational time may be needed to smooth the results. Nonetheless, the heat flux profile tendency can be observed. For this case it reaches a peak around 12000 kW/m² in the stagnation point and slowly decreases as the flow moves downstream of the vehicle.

Figure 9 shows the overall temperature field for the two simulations where the bow shock wave over the capsule is clearly observed. The shock presence is what favors the high variation of aerothermodynamic properties near the vehicle, such temperature or pressure as shown in plots above along the text.

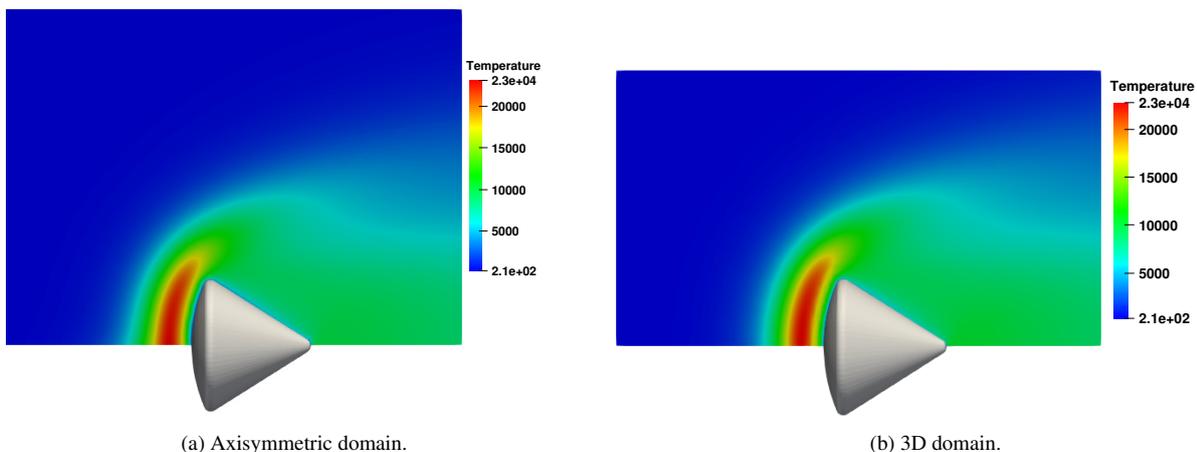


Figure 9. Bow shock fore-body Apollo in both simulations.

5. CONCLUSIONS

In the present study, hypersonic reacting flow over the Apollo capsule was performed at 105 km altitude employing the DSMC technique. In order to obtain the chemical reactions, the Q-K chemistry model with 11 species was employed. Two *dsmcFoamPlus* simulations, an axisymmetric and a three-dimensional were performed providing information concerning the temperature, pressure, density and velocity in three different streamlines along fore-body the capsule.

Data were used to characterize the flowfield around the capsule, allowing to note the presence of a strong bow shock wave fore-body capsule and high temperature profiles due the conversion of kinetic energy in thermal energy. Also, the results showed the importance of accounting the thermochemical nonequilibrium dynamics of the flow, through the use of Q-K model, to properly compute chemical reaction effects on the flowfield properties and to calculate the chemical composition of the gas when effects as dissociation take place.

The results obtained for the axisymmetric and three-dimensional reentry simulations showed good agreement over all the main aerothermodynamic properties analyzed, showing the feasibility of use of the axisymmetric DSMC formulation, at least on the initial stages of the project of space vehicles, to reduce the computational simulation costs when compared to three-dimensional simulations.

6. ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support for this research provided by Agencia Nacional de Investigación y Desarrollo (ANID), under the Research Grants No. 11190068. The authors are also indebted to the support received from Centro Científico Tecnológico de Valparaíso (CCTVal), under the 400 Research ANID PIA/APOYO AFB180002. The results were obtained using the dsmcFoamPlus code and this research was carried out using the computational resources of the Center for Mathematical Sciences Applied to Industry (CeMEAI) funded by FAPESP, Grant No. 2013/07375-0.

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) under the Grants No. 88887.634465/2021-00. The authors also gratefully acknowledge this financial support.

7. REFERENCES

- Allen, A.J. and Eggers, A.H., 1958. "A study of the motion aerodynamic heating of ballistic missiles entering the earth's atmosphere at high supersonic speeds". NACA Report - 1381.
- Bird, G.A., 1979. "Simulation of multi-dimensional and chemically reacting flows". In *11th International Symposium on Rarefied Gas Dynamics*.
- Bird, G.A., 1981. "Monte-carlo simulation in an engineering context". In *12th International Symposium on Rarefied Gas Dynamics*. Charlottesville, VA, US.
- Bird, G.A., 1994. *Molecular Gas Dynamics and the Direct Simulation of Gas Flows*. Oxford Science Publications, New York.
- Bird, G.A., 2011. "The q-k model for gas-phase chemical reaction rates". In *AIP Physics of Fluids 23*. United States.
- Foundation, T.O., 2021. *OpenFOAM*. England.
- Jr, J.D.A., 2003. *Modern Compressible Flow*. McGraw Hill, New York.
- Lietchy, D.S. and Lewis, M.J., 2011. "Extension of a kinetic-theory approach for computing chemical-reaction rates to reactions with charged particles". In *AIP Conference Proceedings 1333*. United States.
- Moss, J.N., Glass, C.E. and Greene, F.A., 2006. "Dsmc simulations of apollo capsule aerodynamics for hypersonic rarefield conditions". In *9th AIAA/ASM Thermophysics and Heat Transfer Conference*. San Francisco, CA, US.
- Palharini, R.C., 2014. *Atmospheric Reentry Modelling Using an Open-Source DSMC code*. Ph.D. thesis, Department of Mechanical & Aerospace Engineering, University of Strathclyde, Glasgow, Scotland.
- Palharini, R.C. and Azevedo, J.L.F., 2015. "Simulation of chemically reactive gas flows around the sara capsulle: Effects on the flowfield structure". In *23rd ABCM International Congress of Mechanical Engineering*. Rio de Janeiro, Brazil.
- White, C., Borg, M.K., Scanlon, T.J., Longshaw, S.M., John, B., Emerson, D.R. and Reese, J.M., 2018. "dsmcfoam+: An openfoam based direct simulation monte carlo solver". *Computer Physics Communications*, Vol. 224, pp. 22–43.

8. RESPONSIBILITY NOTICE

The authors are solely responsible for the printed material included in this paper.