# THE INFLUENCE OF GAS-SURFACE INTERACTION ON THE BRAZILIAN REENTRY SATELLITE AT RAREFIED CONDITIONS

**Rodrigo C. Palharini, palharini.rc@gmail.com**[1]
**João Luiz F. Azevedo, joaoluiz.azevedo@gmail.com**[1]

[1]Instituto de Aeronáutica e Espaço, DCTA/IAE/ALA, São José dos Campos, SP, 12228-904, Brazil

***Abstract:*** *High speed vehicles flying thought Earth's atmosphere are exposed to different flow regimes and a wide range of very complex phenomena. The presence of strong shock waves and chemical reactions are the main characteristics of such flight conditions and they directly affect the design and production of a reliable thermal protection system (TPS). In addition, as the reacting hypersonic flow moves around the spacecraft it tends to corrode (or smooth out) the TPS surface, rendering it more reflective to the impact of air molecules. These gas-surface interactions govern the transfer of momentum and energy from the gas to the solid surface and, hence, influence the heating rates and pressure loads acting on the vehicle surface. In this scenario, the main focus of the present investigation is to assess the impact of gas-surface interaction on the heat transfer, pressure and skin friction coefficients for the Brazilian Reentry Satellite (SARA) at 95 km altitude. At this altitude, conventional techniques based on continuum formulations are no longer valid and the direct simulation Monte Carlo (DSMC) method should be used to handle problems in the rarefied portion of Earth's atmosphere.*
***Keywords:*** *Atmospheric reentry, Rarefied flows, Chemical reactions, DSMC, SARA*

## 1. INTRODUCTION

The Brazilian Program for Space Activities (AEB, 2012) emphasizes the great importance of the development of a suborbital platform in order to conduct scientific and technological experiments in low gravity environment. This suborbital platform, named SARA (acronyms for Satélite Recuperável Atmosférico) has been developed by the Instituto de Aeronáutica e Espaço at DCTA (Departamento de Ciência e Tecnologia Aeroespacial). This capsule can carry up to 55 kg of scientific equipment, stay in orbit during the execution of the experiments, and return to Earth after the accomplishment of the tasks. In order to guarantee a safe return of the capsule and experiments inside of it, the precise determination of the aerodynamic performance, heating rates, and pressure loads acting on the capsule surface during the reentry becomes necessary. For the particular case of SARA capsule, a few studies are available in the current literature and just some of them is discussed below.

Morgenstern and Moraes Jr. (2003) provided a detailed experimental and numerical numerical investigation of the flowfield in the base region of the capsule. It was observed the formation of two main vortices characterized by a unsteady flow region. The effect of this unsteady perturbation on the flowfield in the external cylindrical region, where the parachute pressure sensors are located, was the main concern of this study. The numerical solution showed good agreement with the experimental data and a better understanding on the wake flowfield characteristics was achieved.

Numerical studies of hypersonic blunt body flows with chemical non-equilibrium were investigated by Guzzo and Azevedo (2010). The main objective of their work was to conceive a comprehensive understanding of the Eulerian/Lagrangian hybrid methodology and to test and validate the code over simple configurations. The results showed a good agreement for the overall flow structure and shock wave position when compared with available literature. In addition, the hybrid code seems to be less influenced by the grid parameters and presented a robust approach for hypersonic problems.

Machado (2012) has presented a computational two-dimensional transient aerodynamic investigation of heating and ablation processes on the Brazilian sub-orbital Platform. Considering the capsule composed by two layers, the stainless steel structure and the thermal protection system, this study was able to capture the temperature peak and to represent the ablation process.

Hypersonic non-reacting gas flow simulations over an axisymmetric version of the SARA capsule were conducted by Santos (2013) for altitude varying from 100 to 80 km altitude. The objective of his work was the investigation of the surface accommodation coefficients on the aerodynamic forces acting on the capsule surface, and of the heat transfer rates to the capsule surface.

Palharini and Azevedo (2015) performed rarefied hypersonic gas flow over the SARA capsule in order to investigated the influence of chemical reactions on surface quantities and shock wave structured. It was found that chemical reactions lead to a significant reduction on the shock wave temperature as well as in heat transfer coefficient.

As the vehicle moves through Earth's atmosphere, it is exposed to high enthalpy chemically reactive flows. In such environment, the thermal protection system tends to be polished by the flow being more reflective to oncoming air molecules from the freestream. In this way, the goal of the present investigation is to assess the influence of gas-surface interactions on the aerodynamic surface quantities of the SARA capsule using the direct simulation Monte Carlo technique.

## 2. COMPUTATIONAL METHOD

In highly rarefied environments (Kn > 0.1) the analysis of gas flows in the non-continuum regime is most naturally conducted using specialized computational techniques that are derived from a statistical mechanical representation of the behavior of individual particles. The most successful of these techniques is undoubtedly the direct simulation Monte Carlo (DSMC) approach, originally proposed by Bird (1994).

The DSMC technique instructs particles to move and collide using kinetic-theory considerations that can capture the non-equilibrium gas behavior accurately. DSMC considers molecular collisions using stochastic rather than deterministic procedures over a time step which is a small fraction of the mean collision time, and each DSMC particle represents a large number of real gas molecules. The decoupling of particle ballistic motion and particle collisions improves the computational efficiency of DSMC greatly in comparison with other particle methods such as molecular dynamics (MD). The computational domain is divided into either a structured or unstructured grid of cells, with each cell of a dimension that is a small fraction of the local mean free path size. The cells are then utilized to select particles for collisions on a probabilistic basis, and they are also used for sampling the macroscopic flow properties. Intermolecular collisions are handled probabilistically using phenomenological models which are designed to reproduce real fluid behavior when the flow is examined at the macroscopic level. The DSMC technique has been shown to provide a solution to the Boltzmann equation as the number of simulated particles tends toward the true value within the flow field (Wagner, 1992). The DSMC approach is currently the dominant numerical method for rarefied gas flow applications.

In the DSMC methodology, particle clusters must be endowed with the correct properties to capture kinetic and rotational modes of energy storage. Vibrational excitation of the gas molecules as well as dissociation of both oxygen and nitrogen are likely to be important features of the flow around any hypersonic vehicle at the highest altitudes (80-120 km) and speeds, while, even at lower speeds and altitudes, vibrational excitation and limited dissociation of oxygen are still likely to be important (Anderson, 2006). Such real-gas effects need to be properly accounted for. In the present work, the quantum kinetic (Q-K) chemistry model is used to perform chemically reactive gas flow over the SARA capsule. This model describe the chemical reactions in a 5-species air model based solely on microscopic gas considerations (Bird, 2011; Gallis *et al.*, 2009; Bird, 2008; Wysong *et al.*, 2012; Scanlon *et al.*, 2015). The vibrational energy mode plays a key role in chemical reactions in the Q-K model. The vibrational modes of a gas are normally active when the system is sufficiently energized, e.g., under the high enthalpy conditions combined with shock structures commonly found in hypersonic applications. The vibrational mode forms part of the total energy budget and limits the amount of post-collision energy available to the translational and rotational modes. In addition, it often introduces a new mode of non-equilibrium to a rarefied gas system as the number of collisions required for vibrational relaxation is significantly higher than that for translational or rotational equilibrium (Gallis *et al.*, 2009). The full set of chemical reactions and its implementation into the dsmcFoam code is described by Scanlon *et al.* (2015).

### 2.1 GAS-SURFACE INTERACTION MODEL

The first gas-surface interaction model for kinetic theory was proposed by Maxwell (1879). In this model, two types of interactions are considered: specular and diffuse. Specular reflection is perfectly elastic with the particle velocity component normal to the surface being reversed, while those parallel to the surface remain unchanged. Thus, the angle of reflection is the same as the angle of incidence. Usually, the specular boundary condition is considered to represent a perfectly smooth surface or symmetry plane.

A diffuse reflection represents a microscopically rough surface in which the particle's post-interaction velocity is not related to its pre-interaction velocity. The post-interaction velocity is computed based on thermal equilibrium with the local surface temperature and the direction of the velocity vector is chosen with equal probability in all directions according to the Maxwellian distribution function. In the diffuse gas-surface interaction model just a single accommodation coefficient is required and the scattering angle is independent of the particle's incoming angle. A schematic view of the diffuse and specular gas-surface interactions is shown in Fig. 1.

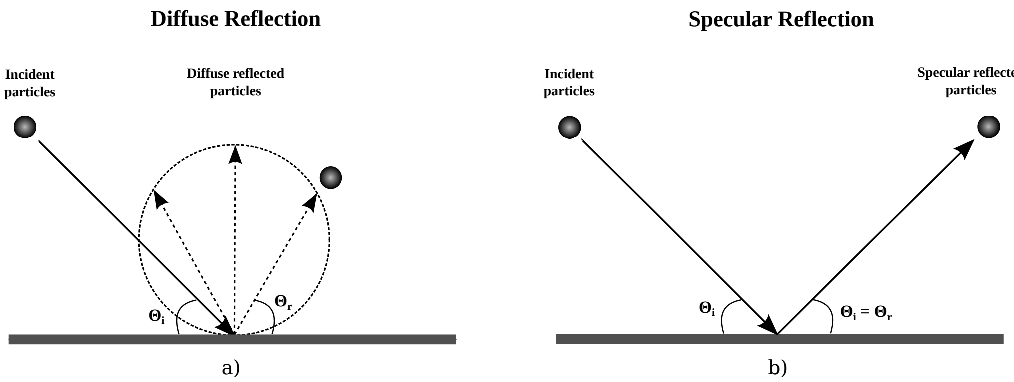



Figure 1: Gas-surface interaction model: a) diffuse reflection and b) specular reflection.

Nowadays, ablative materials are commonly used as thermal protection system for reentry vehicles. This materials depends on their ability to dissipate large amount of heat with only a small amount of material loss. However, during ablation process there may occur an appreciable change in roughness of TPS surface exposed to high enthalpy flow having a significant impact on the aerothermodynamic loads that the vehicle is exposed. In order to mimic different types of surface roughness, a mixed specular-diffuse gas-surface interaction model is used in the present investigation. In this gas-surface interaction model, it is possible to control the amount of molecules that are diffusively or spectacularly reflected from the vehicle surface.

## 3. GEOMETRY DEFINITION AND FREESTREAM CONDITIONS

A detailed representation of the Brazilian Reentry Satellite is shown in Fig. 2. SARA was designed based on the cone-sphere configuration in which the nose radius ($R_n$) is 0.2678 m and 11.4° half-angle conical afterbody. The total length of the capsule is 1.410 m with a base radius of 0.5035 m. All the simulations were performed at 0° angle of attack, i.e., the incoming freestream is parallel to the x-axis.

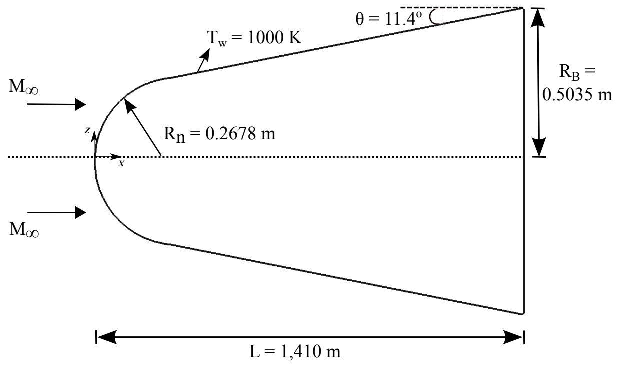



Figure 2: Schematic view of the SARA capsule.

The freestream conditions used in the present investigation correspond to those experienced by the Brazilian reentry capsule at 95 km altitude. The main flow features can be accessed in the U.S. Standard Atmosphere tables (NOAA/NASA/USAF, 1976) and for the particular altitude investigated these informations are tabulated in Tab. 1.

At 95 km altitude, the atmosphere is composed by 78.351% $N_2$, 20.141% $O_2$, and 1.508% O. The freestream mean free path, $\lambda_\infty$, was determined by the variable hard sphere molecular model (Bird, 1983). The overall Knudsen number, K$n$, is defined as the ratio of the molecular mean free path to a certain characteristic dimension. Considering the SARA's nose radius as the characteristic dimension, the Knudsen number correspond to 0.153 and lies in the transition regime. The Reynolds number, $Re_{Rn}$, based on the freestream conditions and calculated considering the nose radius as the characteristic length, is 232.71. Therefore, this is clearly a hypersonic laminar flow. The reentry velocity is set at 7860 m/s for the dsmcFoam computations and established based on the velocity-altitude-map presented by Pessoa Filho (2008).

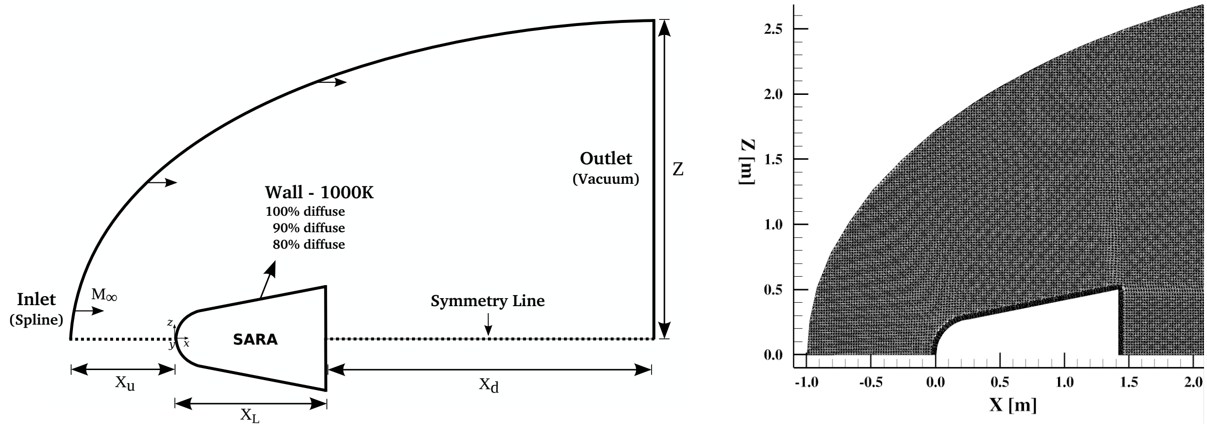
Table 1: Freestream conditions experienced by the SARA capsule at 95 km altitude.

| Parameters | Mach | Re | $U_\infty$ [m/s] | $T_\infty$ [K] | $n_\infty$ [m$^{-3}$] | $\rho_\infty$ [kg/m$^3$] | $p_\infty$ [Pa] | $\lambda_\infty$ [m] |
|---|---|---|---|---|---|---|---|---|
| Values | 28.45 | 232.71 | 7860 | 188.42 | $2.92\times10^{19}$ | $1.39\times10^{-6}$ | $7.59\times10^{-2}$ | $4.11\times10^{-2}$ |

## 4. COMPUTATIONAL DOMAIN AND BOUNDARY CONDITIONS

In the present investigation, advantage is taken from SARA's axisymmetry in order to reduce the computational costs. As shown in Fig. 3, the undisturbed freestream conditions is imposed 1.0 m upstream ($X_u$) of the SARA stagnation point, and the computational domain normal to the probe extended to a distance of 3.0 m in the $y-$ and $z-$directions. To include the wake region in the simulations, the outlet boundary condition is positioned to a distance of 3.09 m from the SARA base ($X_d$).

After the creation of the cubic mesh and the definition of the boundary conditions, the OpenFOAM mesh utility called $snappyHexMesh$ is used to 'snap' the mesh on to the SARA CAD geometry growing hexahedral cells over the surface. After this process, a total of 3.2 million cells are used in the dsmcFoam calculations. The computational mesh is filled with 64.3 million DSMC particles. Freestream conditions are applied at the inlet of the computational domain, represented as a spline in Fig. 3(a). The flow at the downstream outflow boundary is supersonic and vacuum conditions are specified (Bird, 1994). The two perpendicular planes on the side of the capsule represents the symmetry planes, where all flow gradients normal to the plane are zero. At the molecular level, this boundary condition is equivalent to a specular reflecting wall. The wall temperature is kept constant at 1000 K with the gas-surface interaction is modeled in three different ways: i) 100% diffuse, ii) 90% diffuse and 10% specular, and iii) 80% diffuse and 20% specular. Here, the diffuse wall boundary condition is considered with full thermal and momentum accommodation.




(a) (b)

Figure 3: a) Computational boundary conditions, and b) amplified view of SARA computational mesh.

## 5. COMPUTATIONAL RESULTS AND DISCUSSIONS

The influence of gas-surface interaction on the aerodynamic surface quantities is analyzed in this section. Aerodynamic surface quantities are identified by the heat flux, and the normal and tangential forces acting on the vehicle surface.

### 5.1 Aerodynamic Surface Quantities

The heat transfer coefficient $C_h$ is defined as

$$C_h = \frac{q_w}{\frac{1}{2}\rho_\infty U_\infty^3} \tag{1}$$

where the heat flux $q_w$ to the body surface is calculated as the net energy flux of molecules impinging on the surface. A flux is regarded as positive if it is directed towards the body surface. The net heat flux, $q_w$, is related to the sum of the translational, rotational and vibrational energies of both incident and reflected particles, as defined by

$$q_w = q_i - q_r = \frac{F_N}{A\Delta t}\sum_{j=1}^{N}\left\{\left[\frac{1}{2}m_j c_j^2 + e_{Rj} + e_{Vj}\right]_i - \sum_{j=1}^{N}\left[\frac{1}{2}m_j c_j^2 + e_{Rj} + e_{Vj}\right]_r\right\} \tag{2}$$

where $F_N$ is the number of real molecules represented by a single simulated particle, $\Delta t$ is the time step, $A$ the cell surface area, $N$ is the number of particles colliding with the surface per unit time and unit area, $m$ is the mass of the particles, $c$ is the particle velocity, and $e_R$ and $e_V$ are the rotational and vibrational energies, respectively. Subscripts $i$ and $r$ refer to incident and reflected particles.

The heat transfer coefficient ($C_h$) is shown in the Figs. 4(a) and 4(b) along the SARA surface (S). In this set of plots, the $C_h$ is measured from the stagnation point to the base of the capsule and normalized by the SARA nose radius ($R_n$). From this plots, it is clear noticed two distinct regions; the first region which represent the spheric nose (X ≈ 1) and the second region, from X = 1 to X = 5.25, defined as the conical body of the SARA capsule with a circular base.

According to Fig. 4(a), the heat transfer coefficient is most severe at the stagnation point and decreases as the flow moves around the capsule nose. It is observed that $C_h$ is almost constant along the cylindrical body and reach minimum value at the base. From Fig. 4(b), it is clear noticed the influence of the gas-surface interaction on the heat transfer coefficient. When the gas-surface interaction is set as 100% diffuse, an increase of 14.52% on $C_h$ is observed when compared with a surface which gas-surface interactions is chosen to be 80% diffuse and 20% specular. As the degree of wall specularity is increased, flow energy is partially transferred to the spacecraft surface with consequent reduction on the heating rates experienced by the capsule.

The pressure coefficient $C_p$ is defined as:

$$C_p = \frac{p_w - p_\infty}{\frac{1}{2}\rho_\infty U_\infty^2} \tag{3}$$

where the pressure $p_w$ on the body surface is calculated as the sum of the normal momentum fluxes of both incident and reflected molecules at each time step, i.e.:

$$p_w = p_i - p_r = \frac{F_N}{A\Delta t}\sum_{j=1}^{N}\{[(mc_n)_j]_i - [(mc_n)_j]_r\} \tag{4}$$

where $c_n$ is the normal component of the velocity of the DSMC particles $j$.

The impact of the gas-surface interaction on the pressure coefficient $C_p$ is demonstrated in Figs. 4(c) and 4(d) as a function of the arc length S/$R_n$. Looking at these plots, it is observed that $C_p$ follow the same trend as that presented by the heat transfer coefficient, Fig. 4(a). The pressure coefficient is maximum in the stagnation region, decreases up to the point where the spheric nose connects to the conical body. Along this surface, $C_p$ is constant and twice the one found at the stagnation point.

Turning to Fig. 4(d), it is seem that the decreases on the wall diffusivity, from 100% to 80/%, contributes to the increase on the $C_p$ along the SARA spheric nose. The maximum value of 1.98 occurs at position the stagnation point for the gas-surface interaction set as 80/% diffuse and 20% specular with a decrease 3.91% when compared with a fully diffuse wall.

The skin friction coefficient $C_f$ is defined as:

$$C_f = \frac{\tau_w}{\frac{1}{2}\rho_\infty U_\infty^2} \tag{5}$$

where the shear stress $\tau_w$ on the body surface is calculated as the sum of the tangential momentum fluxes of both incident and reflected molecules impinging on the surface at each time step,

$$\tau_w = \tau_i - \tau_r = \frac{F_N}{A\Delta t}\sum_{j=1}^{N}\{[(mc_t)_j]_i - [(mc_t)_j]_r\} \tag{6}$$

where $c_t$ is the tangential velocity component of the velocity of the DSMC particle $j$.

The depends on the skin friction coefficient on the gas-surface interaction is shown in Figs. 4(e) and 4(f) for the wall boundary condition set as 100%, 90%, and 80% diffuse, respectively.

On examining Fig. 4(e), $C_f$ is low at the stagnation region, increases to a maximum value at position S/$R_n$ = 0.26 on the spherical nose and decreases downstream along this surface up to the sphere/cone junction point. The skin friction coefficient is decreases monotonically along the conical body and do not depends on the gas-surface interaction imposed as wall boundary boundary condition. It is also seem from Fig. 4(f), that an increase of the wall spectacularly led to decrease of 12.4% on the peak of skin friction coefficient on the SARA spherical nose.

## 6. CONCLUDING REMARKS

Hypersonic rarefied flows simulations over the SARA capsule is performed using the direct simulation Monte Carlo method. The reactive gas flow is modeled employing the “Quantum Kinetic” chemistry model which take into account the air composed by five species and is able to perform 19 reactions, including dissociation and exchange reactions. The gas-surface interaction imposed as boundary condition is a mixed of diffuse and specular wall. In the present investigation, the degree of wall diffusivity is set as 1, 0.9, and 0.8. All the simulations were performed for SARA reentry point at 95 km altitude.

The analysis of the computational results shows that the peak of heat transfer and pressure coefficients occurs at the stagnation region and decrease downstream as the flow expands around the SARA conical body. However, the peak of shear stress occurs at position S/$R_n$ = 0.26, between the stagnation point and the sphere/cone junction.

The gas-surface interaction model demonstrates to have a significant impact on the aerodynamic surface quantities of the SARA capital. By reducing the degree of wall diffusivity, from 100% to 80%, an decrease of 14.5% and 12.4% is found for the heat transfer and skin friction coefficients. Nonetheless, an increase of 3.91% on the pressure coefficient is observed when the wall boundary condition is set to be 80% diffuse and 20% specular.

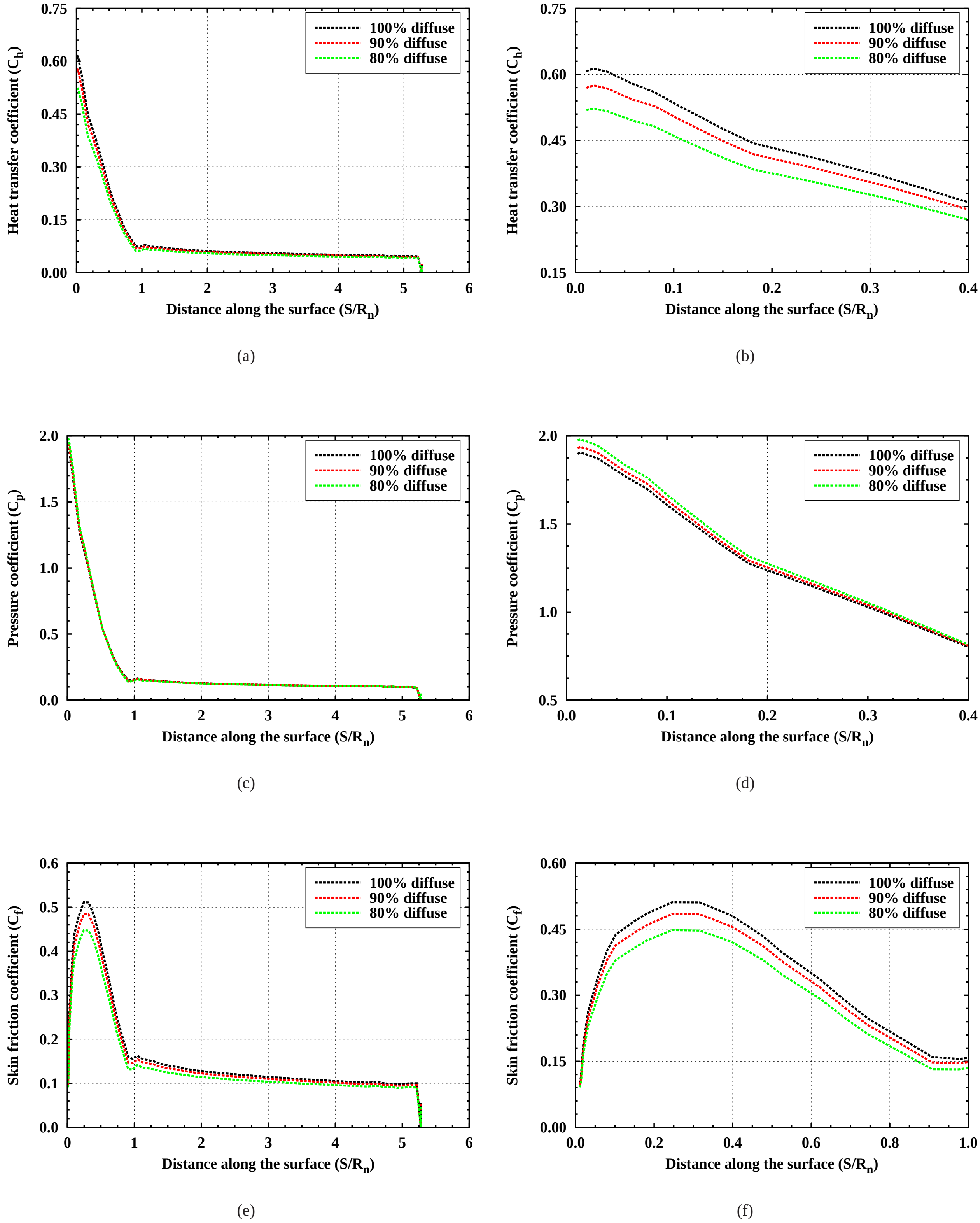



Figure 4: Heat transfer ($C_h$), pressure ($C_p$), and skin friction ($C_f$) coefficients along the SARA surface (left), and amplified view of the measured coefficients along the SARA spheric nose.

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