Effect of Obstacle’s Length-to-Height Ratio on Aerodynamic Quantities of Rarefied Hypersonic Flow

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Abstract. The DSMC method was used to calculate and analyse the flow field structure and the surface aerodynamic quantities when the hypersonic rarefied gas flow passing obstacle at a height of 70km. The changes of surface aerodynamic quantities such as skin friction coefficient, heat transfer coefficient, and pressure coefficient when the length-to-height ratio of the rectangular obstacle is 1/1, 1/2, 1/3, and 1/4 are analysed. The results show that under the above aspect ratio of the obstacle, a recirculation region is formed at each corner of the obstacle. A bow shock will be formed on the windward side of the obstacle, and with the increase of the obstacle’s height, the bow shock will be superimposed on the separated shock wave in front. A strong expansion wave will be formed on the backside of the obstacle, which affects the downstream flow field structure and aerodynamic quantities. When the obstacle’s height increases, the maximum value of the aerodynamic quantities on each surface of the obstacle will increase significantly. It is calculated that the quantities such as heat transfer coefficient and pressure coefficient reach the maximum at the convex point of the windward surface.

1. Introduction

The knowledge of the factors that affect the aerodynamic and thermal loads acting on the vehicle surface becomes significant while designing a hypersonic vehicle. And the hypersonic spacecraft flying in the upper atmosphere inevitably has geometric surface discontinuities, such as cavities, gaps, steps or obstacles, which occurs as a desired or undesired design feature in modern aerodynamic configurations. The obstacles, for example, may be formed due to sensor installations, fabrication tolerances, and differential expansion or ablation rates between different materials [1]. These discontinuities, due to the interaction with external flows, may constitute a potential source in heat flux rise to the surface and may contribute to physical phenomena related to the problem of flow separation.

The flow over a cavity, gap or obstacle causes locally thermal and aerodynamic loads that may seriously exceed those of a smooth curve in hypersonic flight. For safety reasons, these loads must be predicted correctly. This can be done either by experiments, which are very expensive and time consuming for real flight conditions, or by numerical simulation, which is getting constantly increasing importance.

In this context, forward-facing steps positioned in a rarefied hypersonic flow has been studied by Leite and Santos [2] using the DSMC method. The study was inspired by the concern in investigating the impact of frontal-face height on the flow field structure and on the aerodynamic surface properties in the transition flow regime. The computational results suggested that the diversity of the step height
led to significant changes in the flow field structure ahead of the step. High pressure and heating loads were noticed in the vicinity of the step frontal face because of the recirculation region ahead the step.

In the following, Paolicchi and Santos [3] worked on gaps positioned in a rarefied hypersonic flow also by using the DSMC method. The work attempt to investigate the impact of length-to-depth ratio \( (L/H) \) on the flow field structure. The primary highlight was to analyse the behavior of the primary properties, such as pressure, velocity, temperature and density when the gap \( L/H \) ratio changes. The results showed that the gap flow in the transition flow regime acts differently from that found in the continuum flow regime. It was observed only one vortex for the \( L/H \) ratio of 1, 1/2, 1/3 and 1/4. However, in the continuum flow regime, the number of vortices inside the gap is almost given by the amount \( H/L \) [4].

In the present report, numerous studies have attempted to investigate the previous work [2-3]. For example, Leite and Santos have studied on a surface discontinuity, a combined gap/step, in a rarefied hypersonic flow [5], and a back-facing step in the same condition [6]. However, few writers have been able to draw on any systematic research into the geometric discontinuity as an obstacle in the hypersonic rarefied flow. Therefore, the primary goal is to provide a comprehensive characterization of the effects on pressure and heating loads in the flow field structure and on the obstacle surfaces. Freestream flow conditions employed in the present calculations are those given in the previous work [2-3], and represent those experienced by a re-entry vehicle at an altitude of 70 km with freestream Mach number 25. In these conditions, the degree of molecular non-equilibrium is such that the Navier-Stokes equations are inapplicable. Therefore, the DSMC method will be employed to calculate the hypersonic flow on the obstacle configuration.

2. Computational method and procedure
The Direct Simulation Monte Carlo (DSMC) method, developed by Bird [7], has been proved very outstanding in simulating complex physical phenomena in rarefied non-equilibrium flows. The DSMC method using a computer to model real gas flows by simulating a great number of modeling particles, which represents a fixed number of real gas molecules. The states of simulated particles are stored and modified with each time step as the particles move, collide and exit boundary in the simulated domain, so that the position coordinates, velocities and other physical properties such as internal energy can be calculated. In this scenario, the DSMC method will be employed in the present work in order to perform a parametric study of hypersonic rarefied flow over obstacles.

In the present work, the molecular collisions are modeled by using the variable soft sphere (VSS) molecular model, which is proved to be more accurate than variable hard sphere (VHS) [8], and the no time counter (NTC) collision sampling technique [9], and the Borgnakke–Larsen statistical model [10] for energy exchange between translational and internal modes of diatomic or polyatomic molecules. Simulations are operated by using a non-reacting gas model consisting of two chemical species, \( N_2 \) and \( O_2 \). Energy exchanges between the translation and internal modes, rotation and vibration, are considered. Relaxation collision numbers are obtained in a collision energy-based procedure as suggested by Boyd [11] for rotation and by Bird [12] for vibration. For a given collision, the probabilities are designated by the inverse of the relaxation numbers, which correspond to the number of collisions necessary, on average, for a molecule to relax.

In order to implement the collisions between a pair of particles, the flow field around the obstacle configuration is divided into an arbitrary number of regions, which are subdivided into computational cells. The cells are further subdivided into subcells, two subcells/cell in each coordinate direction. The cell provides a reference for the sampling of the macroscopic gas properties, such as density, velocity, pressure, temperature, etc., while the subcell is used in order to select collision partners for the establishment of the collision rate. Therefore, the physical space network is used to facilitate the choice of molecules for collisions and for the sampling of the macroscopic flow properties.

2.1. Geometry definition
Figure 1 shows the definition of the geometric model of an obstacle. A zero-thickness flat plate with an obstacle of length $L$ and depth $H$ was assumed. Since the height $H$ of the obstacle is much smaller than the nose radius $R$ of a re-entry spacecraft, the geometric model can reasonably represent the state when the hypersonic spacecraft has a surface protrusion.

Referring to Figure 1, $M_\infty$ stands for the free stream Mach number, $H$ is the obstacle height, $L$ is the obstacle length, $L_u$ is the length of the obstacle upstream surface, and $L_d$ is the length of the obstacle downstream surface. The following were assumed: $L_u$ and $L_d$ of 45.15 mm, a length $L$ of 3 mm, and a height $H$ of 3, 6, 9, and 12 mm. Therefore, the obstacles investigated correspond to a length-to-height ratio, $L/H$, of 1, 1/2, 1/3, and 1/4, respectively. In addition, $L_u$ and $L_d$ correspond to 50$\lambda_\infty$, where $\lambda_\infty$ is the freestream mean free path at an altitude of 70 km.

An understanding of the $L/H$ ratio effects on the aerodynamic surface properties can be gained by comparing the flow field behavior of a flat plate with an obstacle to that without an obstacle. In this manner, a flat plate without an obstacle works as a benchmark for the cases with an obstacle and will be referred herein as the flat-plate case. For convenience, it was assumed a flat plate with a total length of 200$\lambda_\infty$.

2.2. Freestream and flow conditions

| Parameter         | Value       | Unit          |
|-------------------|-------------|---------------|
| Altitude          | 70          | km            |
| Velocity ($U_\infty$) | 7456        | m/s           |
| Temperature ($T_\infty$) | 220.0       | K             |
| Pressure ($p_\infty$) | 5.582       | N/m$^2$       |
| Density ($\rho_\infty$) | 8.753×10^{-5} | kg/m$^3$     |
| Viscosity ($\mu_\infty$) | 1.455×10^{-5} | Ns/m$^2$    |
| Number density ($n_\infty$) | 1.8209×10^{21} | m$^3$        |
| Mean free path ($\lambda_\infty$) | 9.03×10^{-4} | m            |

Freestream flow conditions used for the numerical simulations are summarized in Table 1. These freestream conditions represent those experienced by a spacecraft at an altitude of 70 km [13]. This altitude is associated with the rarefied flow regime, which is characterized by the overall Knudsen number the order of or larger than $10^{-2}$. In addition, the gas properties, associated with the working fluid, $N_2$ and $O_2$, are given by Bird [7], and tabulated in Table 2. In this table, $m$, $d$, and $\omega$ stand for molecular mass, molecular diameter, and viscosity index, respectively.

|          | m(kg)       | d(m)           | $\omega$ |
|----------|-------------|----------------|----------|
| $O_2$    | 5.312×10^{-26} | 4.07×10^{-10} | 0.77     |
| $N_2$    | 4.650×10^{-26} | 4.17×10^{-10} | 0.74     |

The freestream velocity $U_\infty$, assumed to be constant at 7456 m/s, corresponds to a freestream Mach number $M_\infty$ of 25. The wall temperature $T_w$ was fixed at 880 K, and assumed to be uniform on the obstacle. This temperature is representative of the surface temperature near the stagnation point of a re-entry capsule.

The degree of rarefaction of the flow is usually expressed through the overall Knudsen number, $K_n = \lambda/l$, where $\lambda$ is the mean free path in the freestream gas and $l$ is a characteristic length of the flow...
field. By assuming the obstacle length $L$ as the characteristic length, the overall Knudsen number $Kn_H$ corresponds to 0.3095, 0.1548, 0.1032, and 0.0774 for height $H$ of 3, 6, 9, and 12 mm, respectively. In addition, the Reynolds number $Re_H$ is around 121, 243, 365, and 486 for height $H$ of 3, 6, 9, and 12 mm, respectively, also based on conditions in the undisturbed stream.

2.3. Computational flow domain and grid

![Figure 2. Schematic view of the computational domain.](image)

The physical space around the obstacle was divided into four regions, which were subdivided into computational cells, in order to improve the choice of particles for collisions and for sampling of the macroscopic flow properties. According to previous studies [14-15], the size of each cell should be smaller than the local mean free path $\lambda_{\infty}$, which provided a proper reference for the sampling of the macroscopic gas properties. Also, cells were further subdivided into subcells on the basis of the number of simulated particles, by two subcells per cell in each coordinate direction, in order to ensure physical accuracy in the collision process. In this case, the collision partners were chosen from the same subcell for the establishment of the collision rate. For a given pair of particles, the collision probabilities are inversely proportional to the relaxation numbers, which correspond to the number of collisions necessary, on average, for a molecule to achieve thermal equilibrium.

A schematic view of the computational domain is plotted in Figure 2. This computational domain was made large enough so that flow disturbances caused by the obstacle did not reach the computational boundaries, where freestream conditions were specified. As can be seen in this figure, side IV-A is defined by the obstacle surface. Diffuse reflection with complete thermal accommodation is applied to this side. Side IV-B is a plane of symmetry, where all flow gradients normal to the plane are zero. At the molecular level, this plane is equivalent to a specular reflecting boundary. Sides I and II are the freestream sides through which simulated particles enter and exit. Side I is positioned $5\lambda_{\infty}$ upstream of the flat-plate leading edge, and side II defined at $50\lambda_{\infty}$ in obstacle height $H$ of 3 and 6 mm cases, and $70\lambda_{\infty}$ in $H$ of 9 and 12 mm cases above the flat plate. Finally, at the downstream outflow boundary, side III, the flow is predominantly supersonic, and vacuum condition was specified [12]. Therefore, simulated molecules can only exit at this boundary.

3. Computational results and discussion

This section focuses on the effects that take place in the aerodynamic surface quantities due to variations on the obstacle $L/H$ ratio. Aerodynamic surface quantities of particular interest in the transitional flow regime are heat flux, wall pressure, and shear stress. In this scenario, this section discusses and compares the differences of these quantities expressed in a coefficient form.

Before proceeding with the analysis of the aerodynamic surface quantities, it proves instructive to first present some features of the flow patterns around the obstacles. In doing so, particular attention is paid to the distribution of pressure coefficient in the entire computation domain.
Distribution of pressure coefficient around the obstacle is illustrated in Figure 3. In this plot, pressure is normalized by the freestream pressure, $\rho_\infty$. According to Figure 3, it is observed that the maximum value for the pressure coefficient takes place in a region in the vicinity of the front side of the obstacle. It is obvious that there is a shock wave at the leading edge and a bow shock in front of the obstacle.

![Figure 3. Pressure Coefficient $C_p$ distribution in the vicinity of obstacles.](image)

3.1. Heat transfer coefficient

The heat transfer coefficient $C_h$ is defined as follows:

$$C_h = \frac{q_w}{(1/2)\rho_\infty U_\infty^2}$$

where $q_w$ is the heat flux to the body surface.

The heat flux $q_w$ to the body surface is calculated by the net energy flux of the molecules impinging on the surface. The net heat flux $q_w$ is related to the contribution of the translational, rotational, and vibrational energies of both incident and reflected molecules as defined by the following expression:

$$q_w = q_i - q_r = \frac{E_N}{\Delta t} \left\{ \sum_{j=1}^{N} [\phi_j]_i - \sum_{j=1}^{N} [\phi_j]_r \right\}$$

where $\phi_j = \frac{1}{2} m_j c_j^2 + e_{R,j} + e_{V,j}$, $c$ is the velocity of the molecules, $e_{R}$ and $e_{V}$ stand for rotational and vibrational energies, respectively.

The dependence of the heat transfer coefficient $C_h$ on the $L/H$ ratio is demonstrated in Figure 4 for surfaces S1 and S5, and in Figure 5 for surfaces S2, S3 and S4. As shown in Figure 4, important features can be observed in the heat transfer coefficient $C_h$ along surface S1 due to changes in $L/H$ ratio. Of particular interest, it is observed that the heat transfer coefficient $C_h$ for obstacles follows the same behavior presented by the flat-plate case close to the sharp leading edge, region unaffected by the presence of the obstacles. Further downstream along the surface S1, the heat transfer coefficient $C_h$ significantly increases and reaches peak values close to the frontal face, then decreases to almost zero at the stagnation region. Along the frontal face S2, the heat transfer coefficient increases monotonically, from zero at the stagnation point to a maximum value near the S2/S3 junction, which depends on the frontal-face height $H$. Along the upper surface S3, the heat transfer coefficient presents a maximum value at the S2/S3 junction and then decreases downstream along the surface. It is quite apparent that this significant increase in the heat transfer coefficient is due to the flow reattachment zone. Along the back surface S4, the heat transfer coefficient is two orders of magnitude lower than those observed on the surfaces S1 and S5, which is due to the recirculation region formed in the vicinity of the back face. Along the surface S5, the minimum heat transfer coefficient occurs in the vicinity of the back face in the recirculation region. After that, the heat transfer coefficient increases to a maximum value after the flow reattachment. In the following, $C_h$ almost decays and approaches the level observed for the flat plate without an obstacle.
Figure 4. Heat transfer coefficient $C_h$ distribution along surface S1 and S5

Figure 5. Heat transfer coefficient $C_h$ distribution along obstacle surfaces S2, S3, and S4.

For comparative purpose, the maximum values for $C_h$ are around 0.21, 0.34, 0.43 and 0.46 for height H of 3, 6, 9 and 12mm, respectively. In contrast, the $C_h$ for the flat-plate case, i.e., a flat plate without obstacles, is around 0.0284 at section X = 9.11 in the surface. Therefore, $C_h$ of 0.21, 0.34, 0.43 and 0.46 correspond respectively to 7.39, 11.97, 15.14 and 16.20 times the pick value for the flat-plate case. Furthermore, it is very encouraging to observe that, for H of 12 mm case, the amount of energy transferred to the obstacle corner represents around 50% of the total energy ($\frac{1}{2} \rho u^2$) of the gas coming from the freestream.

Another feature of particular interest in the heat transfer coefficient behavior is related to the peak values on the surface S1 due to the presence of the obstacles. As shown in Figure 4, the maximum values observed for the heat transfer coefficient $C_h$ as well as the location in which they occur depend on the obstacle’s height H. For height H of 3, 6, 9 and 12 the maximum values for the heat transfer coefficient $C_h$ correspond to section X of 46.8, 42.2, 35.7 and 31.1, respectively. For the time being, it is worth taking a closer look at the peak values for the H = 9 and 12 case. Referring to Figure 4, it is clearly noticed a second point of maximum heat transfer coefficient at the vicinity of the obstacle, more precisely for section X = 45.9 and 45.00. This behavior differs from the other two cases, i.e., obstacle height H of 3 and 6 mm.

3.2. Pressure coefficient
The pressure coefficient $C_p$ is defined as follows:

$$C_p = \frac{p_w - p_\infty}{\frac{1}{2} \rho_\infty U_\infty^2}$$  \hspace{1cm} (3)$$

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

$$p_w = p_i - p_r = \frac{F_N}{A \Delta t} \sum_{j=1}^{N} \left[ [(mv)_i]_j - [(mv)]_j \right]$$  \hspace{1cm} (4)$$

where $F_N$ is the number of real molecules represented by a single simulated molecule, $\Delta t$ is the time step, $A$ is the area, $N$ is the number of molecules colliding with the surface per unit time and unit area, $m$ is the mass of the molecules, $v$ is the velocity component of the molecule $j$ in the surface normal direction. Subscripts $i$ and $r$ refer to incident and reflect molecules.

The impact on the pressure coefficient $C_p$ caused by changes in the obstacle’s height $H$ is depicted in Figure 6 for surfaces S1 and S5, and in Figure 7 for surfaces S2, S3 and S4. According to this group of plots, it is noted that the pressure coefficient on the surface depends on the obstacle height, the pressure coefficient behavior along the obstacle surface is similar to that for the flat-plate case at the vicinity of the sharp leading edge. The upstream disturbances in the pressure coefficient $C_p$, due to the presence of the obstacle, were felt up to section $X$ corresponding to approximately 28.27, 32.92, 38.49 and 44.07 for obstacles with height $H$ of 12, 9, 6 and 3, respectively. From these sections up to the obstacle position, $X = 50$, the pressure coefficient $C_p$ increases dramatically when compared to that for the flat-plate case. The maximum values for the pressure coefficient $C_p$ along the surface S1 occur at the stagnation point, at the S1/S2 junction. Along the frontal surface S2, the peak value for $C_p$ occurs close to the S2/S3 junction, similar to that peak value location for the heat transfer coefficient. Along the upper surface S3, the pressure coefficient presents a maximum value at the S2/S3 junction and then decreases downstream along the surface. Along the back surface S4, the smallest values for the pressure coefficient take place along the back face. And in this region, $C_p$ is negative, this behavior is directly

**Figure 6.** Pressure coefficient $C_p$ distribution along surface S1 and S5.

**Figure 7.** Pressure coefficient $C_p$ distribution along obstacle surfaces S2, S3, and S4.
related to the recirculation region downstream of the back face. It should be mentioned in this context that the recirculation region in the vicinity of the back face is a region of low pressure.

Nevertheless, very close to the back corner, the pressure coefficient drops off due to the flow expansion around the back corner. After that, in the vicinity of the back face on surface S5, the pressure coefficient suddenly almost goes down and afterward increases significantly as the flow develops along surface S5. In addition, a significant reduction in the pressure coefficient is observed at the end of the lower surface. The reason for that is associated with the vacuum condition assumed for the downstream outflow boundary, side IV, as explained earlier.

For comparison purpose, the maximum values for $C_p$ on the frontal face are around 0.63, 1.15, 1.59 and 1.80 for height H of 3, 6, 9 and 12, respectively. In contrast, the maximum value of $C_p$ for the flat-plate case, i.e., a flat plate without obstacles is around 0.0393 at section X = 25.96 in the surface. Therefore, $C_p$ correspond respectively to 16.03, 29.26, 40.45 and 45.80 times the pick value for the flat-plate case, which corresponds to a smooth surface.

It is noteworthy that the pressure coefficient rise at the vicinity of the frontal face is directly related to the recirculation zone that forms ahead of the obstacle. This pressure rise is explained by the fact that molecules, confined in the recirculation zone, collide with the surface S1 and with the face S2 of the obstacle, causing an increase in the normal momentum to surfaces of the obstacle. What stands out in Figure 6 is the peak value of pressure coefficient on surface S5, in $L/H$ ratio of 1/2, 1/3 and 1/4 case, the pressure coefficient is 25%-50% higher than the flat-plate case.

### 3.3. Skin friction coefficient

The skin friction coefficient $C_f$ is defined by,

$$
C_f = \frac{\tau_w}{(1/2)\rho_u U_\infty^2}
$$

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

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

where $u$ is the velocity component of the molecule $j$ in the surface tangential direction.

![Figure 8. Skin friction coefficient $C_f$ distribution along surface S1 and S5.](image)
The distribution of skin friction coefficient $C_f$ along the surfaces S1 and S5 is displayed in Figure 8 and the obstacle surfaces S2, S3, and S4 in Figure 9 as a function of the obstacle height $H$. Looking first to Figure 8, it is observed that the upstream disturbances, due to the presence of the obstacles, are felt in the skin friction coefficient $C_f$ approximately up to section X of 27.34, 31.06, 35.7, and 41.2, for height $H$ of 12, 9, 6, and 3, respectively. From this position up to the obstacle position, $X = 50$, the skin friction coefficient $C_f$ decreases, when compared to that for the flat-plate case, and reaches zero for section X of 31.99, 36.63, 42.21, and 48.22 for height $H$ of 12, 9, 6, and 3, respectively. After that, as a result of the recirculation region, the skin friction coefficient $C_f$ continues to decrease up to a minimum point. After the minimum point, $C_f$ increases again and reaches values close to zero at the stagnation point at the base of the obstacle. Along the upper surface S3, the skin friction coefficient $C_f$ presents the maximum value at the obstacle shoulder, then drops off downstream and reaches the value observed for the flat-plate case. Along the surface S5, the skin friction coefficient is negative near to the face of the obstacle and becomes positive at the reattachment point, as shown in the magnified view. After that, the skin friction coefficient increases and reaches the values observed for the flat plate without obstacles.

Turning to Figure 9, along the frontal face S2, the skin friction coefficient $C_f$ is basically zero at S1/S2 junction. After that, it is negative from the obstacle base up to the flow reattachment point. From this point up to the S2/S3 junction, the skin friction coefficient drastically increases, since this is basically a region exposed to a high speed flow. Afterwards, due to the flow expansion around the S1/S2 junction, the skin friction coefficient $C_f$ diminishes by approximately 50% in comparison to the values observed at the beginning of the upper surface. Along the back surface S4, it is seen that the skin friction coefficient $C_f$ along the back face is at least two orders of magnitude smaller than that observed along the upper surface. In addition, the peak values take place at the upper-most portion of the back face. Moreover, peak values decrease by increasing the obstacle height $H$. It should be mentioned that the section corresponding to the condition of $C_f = 0$ ($\tau_w = 0$) was used to define the separation point.

A more careful analysis in the distribution of the skin friction coefficient $C_f$ reveals important flow peculiarities at the vicinity of the S1/S2 corner. As shown in Figure 8, the skin friction coefficient $C_f$ on S1, after reaching the minimum negative value, it increases again and reaches values around zero at the stagnation point. A magnified view of the stagnation region indicates that the skin friction coefficient $C_f$ becomes positive in this region, more precisely at section X of 49.33, 49.34, 49.00 and 48.89 for height $H$ of 3, 6, 9 and 12, respectively, as illustrated in Figure 8. For the time being, it is worth taking a closer look at the peak values for the $H = 9$ and 12 cases. Referring to Figure 8, it is clearly noticed a second point of maximum skin friction coefficient at the vicinity of the obstacle, more precisely for section X = 40.35 and 34.78. This behavior differs from the other two cases, i.e., obstacle height $H$ of 3 and 6 mm.

4. Conclusions
Computations of a rarefied hypersonic flow over obstacles have been performed by using the Direct Simulation Monte Carlo (DSMC) method. The simulations provided information concerning the nature
of the aerodynamic properties acting on the surface of the obstacle. The effects of the obstacle height on the heat transfer, pressure and skin friction coefficients for a representative range of parameters were investigated. The obstacle height ranged from 3 to 12 mm, which corresponded to Knudsen numbers in the transitional flow regime.

The analysis showed that hypersonic flow past an obstacle is characterized by a strong bow-shock ahead of the frontal face, which influences the aerodynamics surface properties upstream the frontal face. And a strong expand wave was formed at the back face of the obstacle, which affects the properties downstream the back face. It was found that the disturbance at both upstream and downstream due to the presence of the obstacles increased with the obstacle height rise. Nevertheless, locally high heating rates were observed on the surface upstream and downstream the obstacle. The simulations showed that these high heating rates are a consequence of the molecules confined in the recirculation zones. As a result, for the conditions investigated in this work, in terms of heat and pressure loads, the presence of a discontinuity like an obstacle on the vehicle surface should be avoided in the vehicle design. And heat protection should be enhanced if an obstacle on the surface is inevitable.

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