Numerical Study of Hypersonic Rarefied-Gas Flows About a Toroidal Ballute

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Abstract. Hypersonic flows of nitrogen, oxygen, argon, and carbon dioxide near a toroidal ballute have been investigated numerically using the Direct Simulation Monte-Carlo technique under transition rarefied-gas flow conditions (Knudsen numbers from 0.005 to 10). Strong influences of the geometrical factor (a ratio of the distance between the axis of symmetry and the torus disk center, and the torus radius) and the Knudsen number on the flow structure (the shape of shock waves and the stagnation point location), skin friction, pressure distribution, and drag have been found.

Keywords: Torus, Balloon Parachute, Transition Rarefied-Gas Flows, Aerodynamic Coefficients.
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NOMENCLATURE

A = torus base area, $4\pi RH$, m^2
C_f = local skin-friction coefficient, $\tau_w/q_\infty A$
C_p = local pressure coefficient, $(p_w - p_\infty)/q_\infty A$
C_x = drag coefficient
D = diameter of a torus disk, 0.2 m
H = distance between the axis of symmetry and the torus disk center, m
H_* = radius of a toroidal model throat, 0.014 m
$Kn_{\infty,D}$ = Knudsen number
M = Mach number
p = pressure, N/m^2
q_∞ = dynamic pressure, $0.5\rho_\infty u_\infty^2$, N/m^2
R = radius of a torus disk, 0.1 m
τ_w = viscous stress at the torus surface, N/m^2

subscripts
D = torus-disk diameter as a length-scale parameter
w = wall condition
∞ = freestream flow parameter.

INTRODUCTION

Numerical and experimental studies of aerothermodynamics of simple-shape bodies have provided valuable information related to physics of hypersonic flows about spacecraft elements and testing devices [1-5]. Numerous results had been found in the cases of plates, wedges, cones, disks, spheres, and cylinders (see Refs. 1-7). Aerocapture with large inflatable decelerators known as toroidal ballutes [8] is currently viewed as the most promising technology for a number of NASA's future robotic missions to Venus, Saturn, Titan, and Neptune [9-11].

In the present study, the hypersonic rarefied-gas flow about a torus has been studied. The flow pattern in argon was discussed in Ref 12. Several features of the flow are unique. For example, if the distance between the axis of symmetry and the torus disk center H is significantly larger the torus radius R, then the flow can be approximated by a stream between two side-by-side cylinders [13, 14]. At $H = R$, the rarefied gas flow has some features of a stream near a bluff disk [5]. In the first case, two conical shock waves would focus and interact in the vicinity of the symmetry axis generating the normal shock wave and the conical reflected waves. The stagnation points would be near the front points of the torus disks. In the second case, the front shock wave would be normal and the location of stagnation points would be difficult to predict. At $H > R$, the flow pattern and shock-wave shapes are very complex. As a result, simple approximation techniques would not be applied in torus aerothermodynamics.

In the present study, flow about a torus and its aerodynamic characteristics have been investigated under the conditions of a hypersonic rarefied-gas stream of nitrogen, argon, dissociating oxygen, and carbon dioxide at $8R \geq H \geq 2R$ and the Knudsen number $Kn_{\infty,D}$ from 0.01 to 10. The numerical results have been obtained using the direct simulation Monte Carlo (DSMC) technique [3]. The computer code was developed by Graeme Bird [15].

DSMC METHOD

The DSMC method [3] is used in this study as a numerical simulation technique for low-density gas flows. The flow parameters are calculated using an axisymmetrical version of the DSMC code [15]. Molecular collisions in nitrogen, argon, oxygen, and carbon dioxide are modeled using the variable hard sphere molecular model [3]. The gas-surface interactions are assumed to be fully diffusive with full energy and moment accommodation. The code validation was tested [5] in comparing numerical results with experimental data [4, 5] for the simple-shape bodies.

In calculations at $H/R = 8$, the total number of cells near a torus (a half-space of the unit segment) is 3000 in three zones, the molecules are distributed nonevenly [2], and a total number of 27,200 molecules corresponds to an average of 9 molecules per cell. Following the recommendations of Refs. 2, 3, and 15, acceptable results are obtained for an average of at least ten molecules per cell in the most critical region of the flow. The error was pronounced when this number fell below five, i.e., flow near the symmetry axis (Figs. 1a and 1b). In all cases the usual criterion [2] for the time step Δt_m has been realized: $2\times10^{-7} \leq \Delta t_m \leq 1\times10^{-6}$ s. Under these conditions, aerodynamic coefficients and gasdynamic parameters have become insensitive to the time step.

The location of the external boundary with the upstream flow conditions varies from 1.0D to 2.0D for different flow conditions. Calculations were carried out on a personal computer. The computing time of each variant was estimated to be approximately 5 - 20 h.

RESULTS

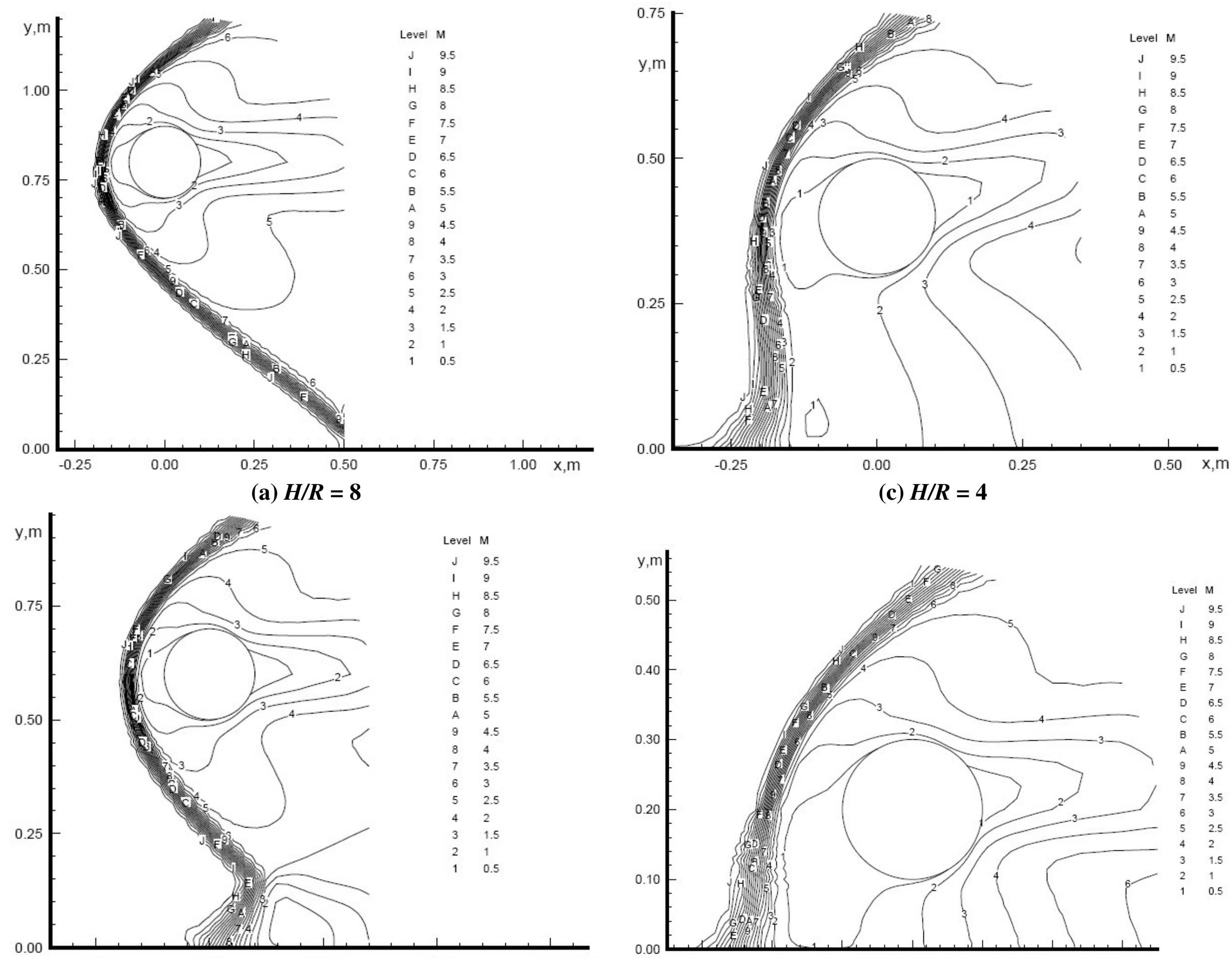
Influence of the Geometrical Factor, *H/R*

The flow pattern over a torus is significantly sensitive to the major geometrical similarity parameter H/R. The influence of this parameter on the flow structure has been studied for hypersonic flow of nitrogen at $M_\infty = 10$ and $Kn_{\infty,D} = 0.01$. It is assumed that the wall temperature is equal to the stagnation temperature.

The local Mach number contours are shown in Fig. 1 for four cases of the geometrical factor (H/R = 8, 6, 4, and 2). At $H/R = 6$, a conical shock wave can be observed near the torus. The interference of the shock waves takes in the form of the normal shock wave (the "Mach disk") in the vicinity of the symmetry axis. At the intersection of the conical and normal shock waves, a new type of conical reflection wave has been found (Fig. 1b). This internal reflection wave would be observed in density, temperature, and velocity contour diagrams (see Ref. 16 for details). The boundaries of a local subsonic zone are restricted by supersonic conical flow behind the conical shock waves and the reflected waves.

The shapes of the front shock waves are different for gases with different ratios of specific heats (Fig. 2). In the flow of argon, a conical shock wave and the Mach disk can be observed right in the torus throat at $H/R = 8$. The flow pattern calculated for the flow of nitrogen mixed with 0.5% O_2 at $H = 0.056$ m, $R = 0.008$ m, density $\rho_\infty = 0.03$ kg/m^3, velocity $U_\infty = 2700$ m/s, pressure $p_\infty = 3.1$ kPa, temperature $T_\infty = 347$ K, and $M_\infty = 7.5$ correlates well with the flow field visualized in the experiment [17] by using the Planar Laser Induced Fluorescence imaging (Fig. 3).

The shock-wave shape and the scale of the subsonic zone behind the shock wave are very sensitive to the geometrical parameter H/R (Fig. 1). At $H/R \leq 4$, the shape of a front shock wave becomes normal, and the subsonic area is restricted by the location of the shock wave and the torus throat (see Figs. 1c and 1d). This effect plays a fundamental role in the redistribution of pressure and skin friction along the torus surface [see Figs. 4a and 4b, correspondingly; the angle θ changes from the torus rear point ($\theta = 0$ deg) in the counterclockwise direction].



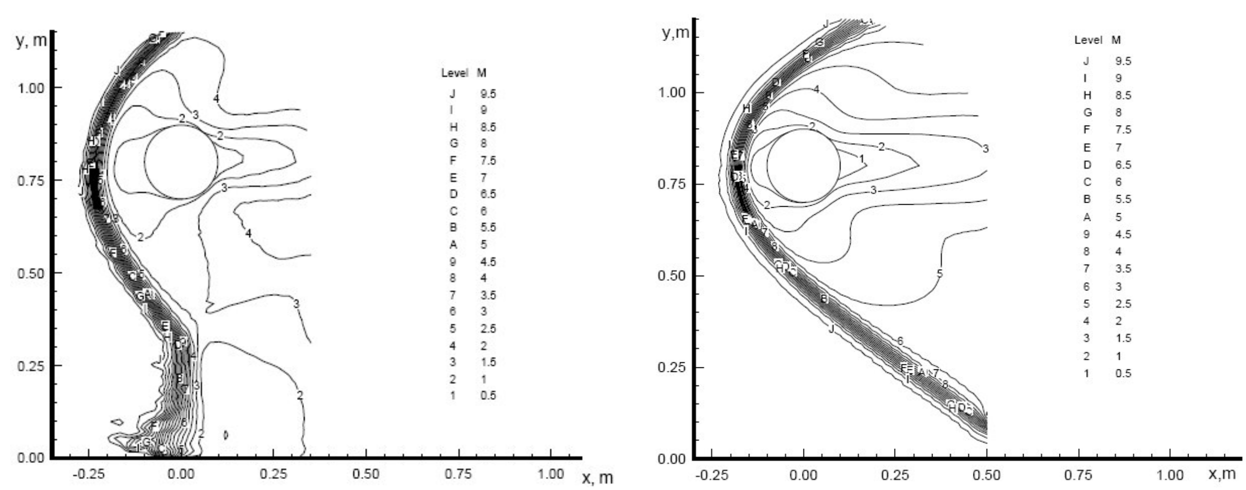
(a) *H/R* = 8

(c) *H/R* = 4

(b) *H/R* = 6

(d) *H/R* = 2

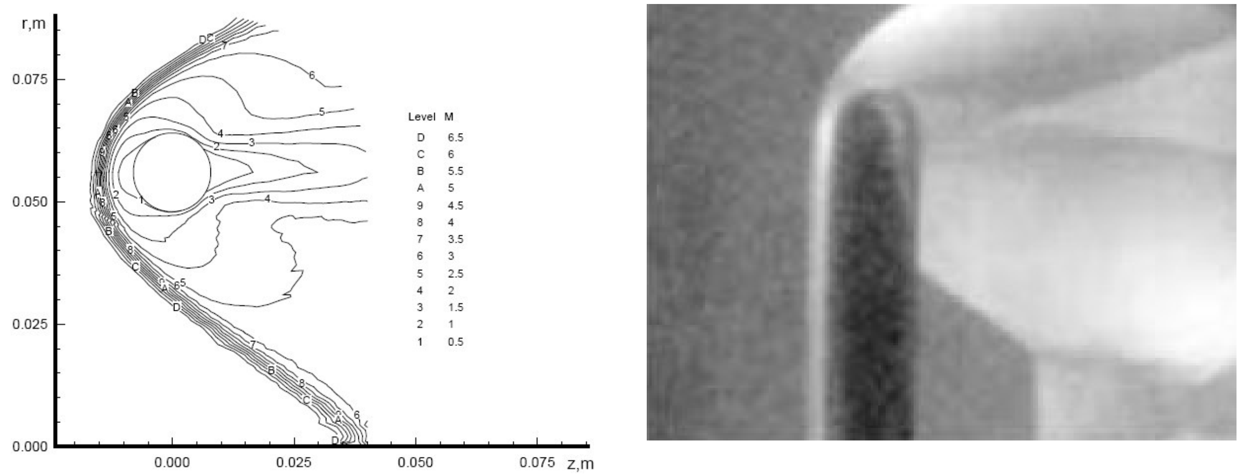
FIGURE 1. Mach number contours in nitrogen flow about a torus at $Kn_{\infty,D} = 0.01$, $M_\infty = 10$, and various geometrical factors *H/R*.



(a) argon flow

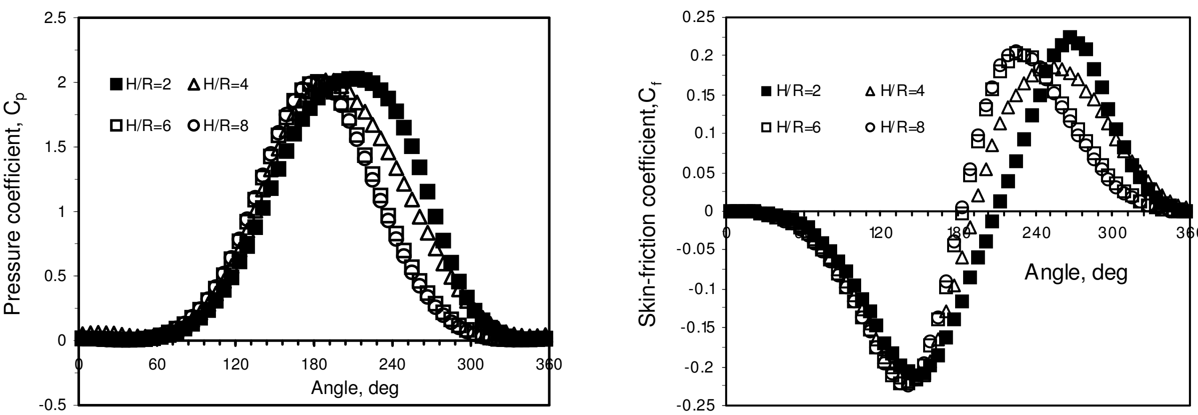
(b) carbon dioxide flow

FIGURE 2. Mach number contours in flows of argon and carbon dioxide about a torus at $Kn_{\infty,D} = 0.01$, $M_\infty = 10$, and *H/R*=8.



(a) DSMC calculation **(b) experiment [17]**

FIGURE 3. Contours of constant Mach numbers near a torus in the flow of nitrogen at $Kn_{\infty,D} = 0.00013$ and $M_\infty = 7.11$.



(a) Pressure coefficient, C_p **(b) Skin-friction coefficient, C_f**

FIGURE 4. Pressure and skin-friction coefficients along the torus surface in nitrogen flow at $Kn_{\infty,D} = 0.01$, $M_\infty = 10$, and various geometric factors *H/R*.

The dynamics of the subsonic zone is a major factor of relocation of the stagnation-point ring in the front area of the torus. The location of the stagnation point is moving from the front area to the torus throat after reducing the outer torus radius. The identical effect can be observed in calculations of pressure and skin-friction coefficients (Fig. 4).

Influence of the Knudsen number, $Kn_{\infty,D}$

The rarefaction factor, which can be characterized by the Knudsen number $Kn_{\infty,D}$, plays an important role in the flow structure [3, 5-7] as well as in aerodynamics [1, 4, 5]. The flowfield about a torus has been calculated for hypersonic flow of nitrogen at $M_\infty = 10$ and the Knudsen numbers $Kn_{\infty,D} = 0.01$, 0.1, 1, and 4.

Under continuum flow conditions ($Kn_{\infty,D} = 0.01$), the flow structure has the same features as were discussed above. In transitional flow regime, at $Kn_{\infty,D} = 1$, the flow pattern is different (Fig. 5). The reflection waves have different shapes, because of the rarefaction effects in the conic and normal shock waves. At a small outer torus radius, *H/R* =2, the skin-friction coefficient distribution along the torus surface becomes sensitive to the rarefaction parameter $Kn_{\infty,D}$ (Fig. 6). The locations of the front stagnation points are also changed at different Knudsen numbers.

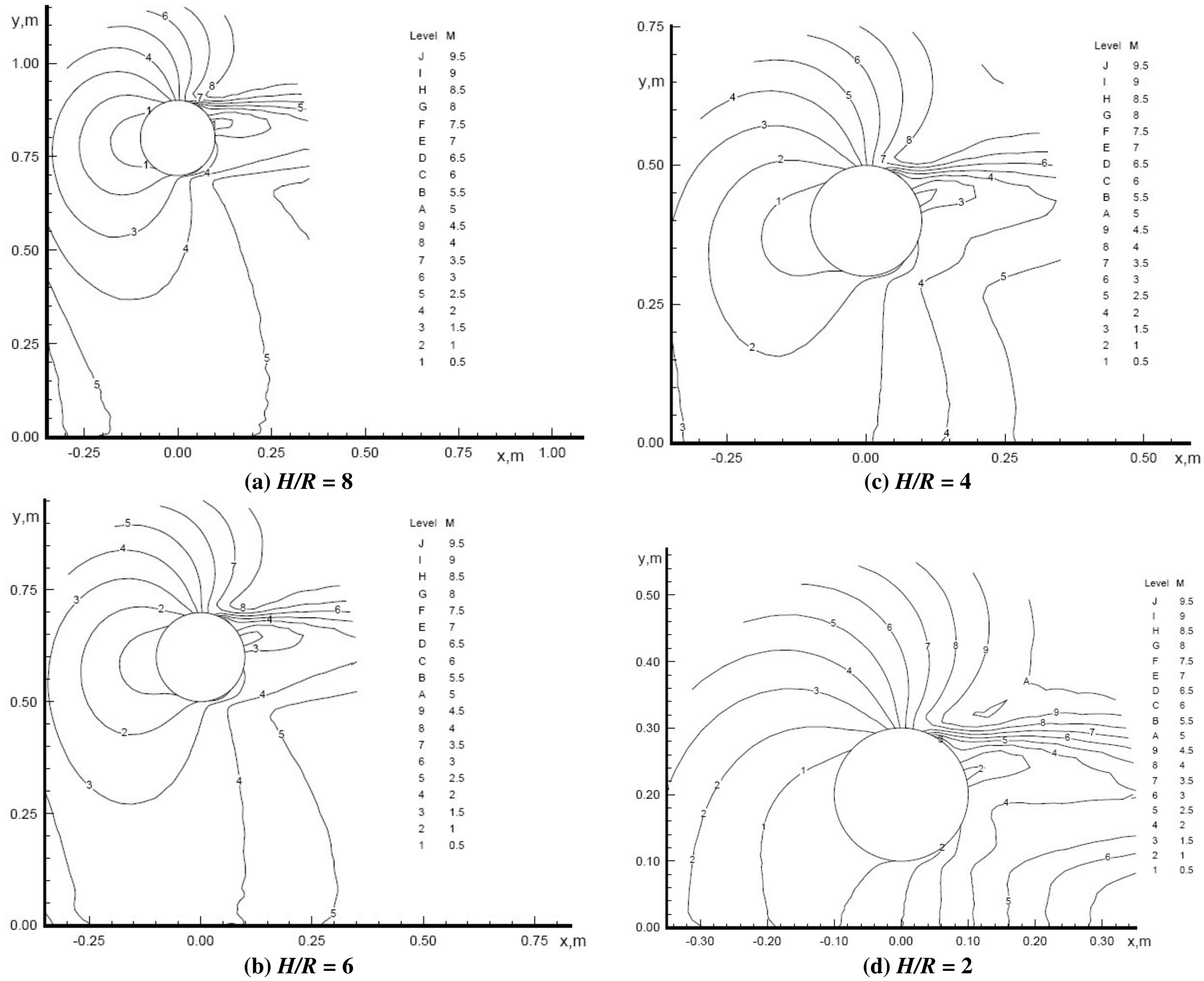


FIGURE 5. Mach number contours in nitrogen flow about a torus at $Kn_{\infty,D} = 1$, $M_\infty = 10$, and various geometrical factors *H/R*.

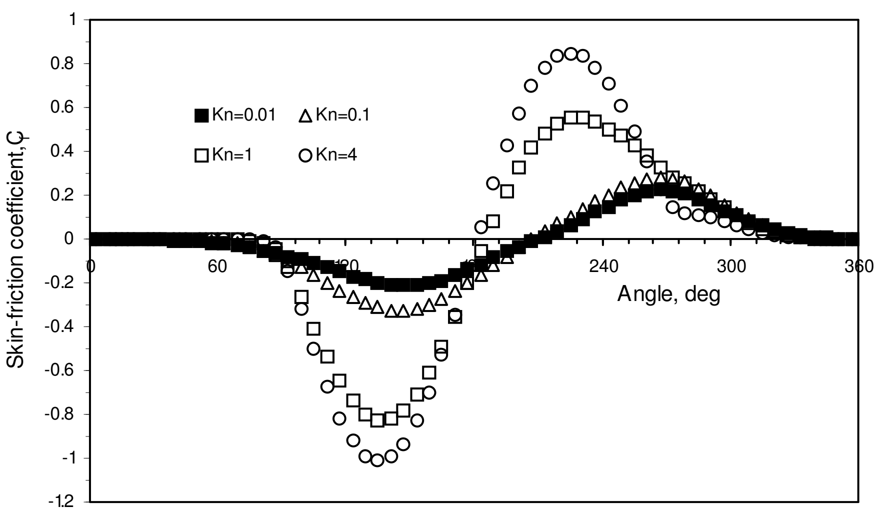


FIGURE 6. Skin-friction coefficient C_f along the torus surface in nitrogen flow at *H/R* = 2, $M_\infty = 10$, and various Knudsen numbers $Kn_{\infty,D}$.

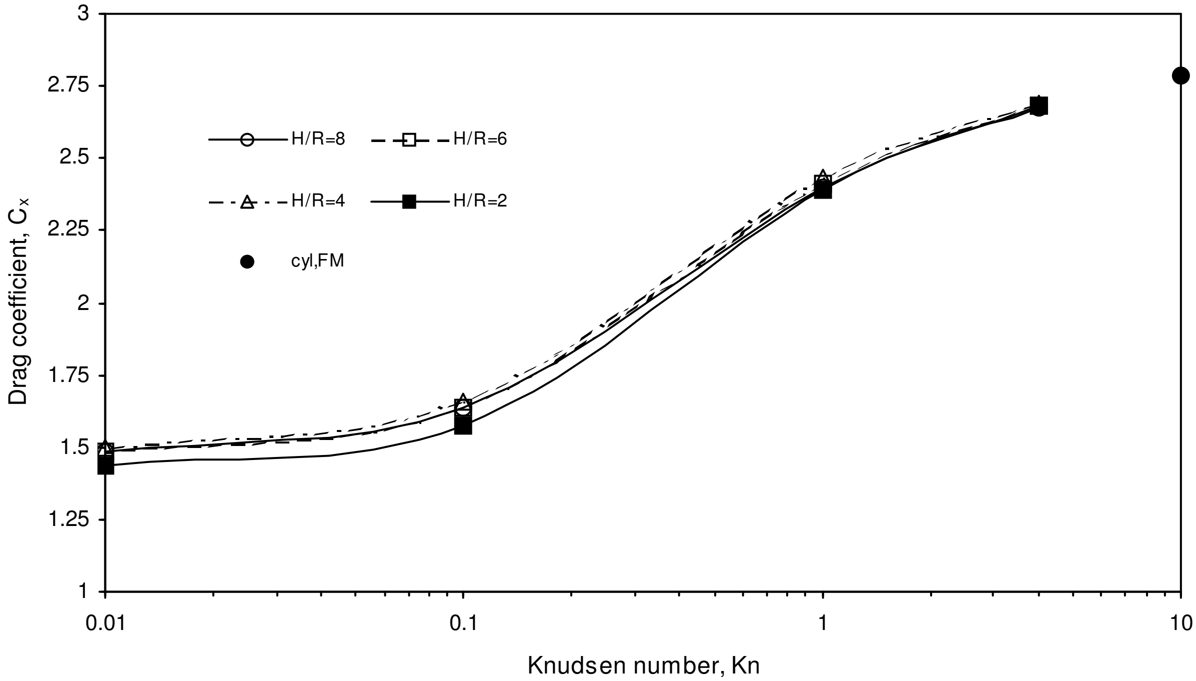


FIGURE 7. Drag coefficient C_x of a torus vs. Knudsen number $Kn_{\infty,D}$ and various geometrical factors *H/R* in the flow of nitrogen at $M_\infty = 10$.

The calculating results of the total drag coefficient are shown in Fig. 7. At any outer-inner radii ratio, the drag coefficient increases with increasing the Knudsen number. The geometrical factor becomes insignificant on the drag at $H/R \geq 6$ under continuum flow regime conditions, and at $H/R \geq 4$ in free-molecule flow regime [18].

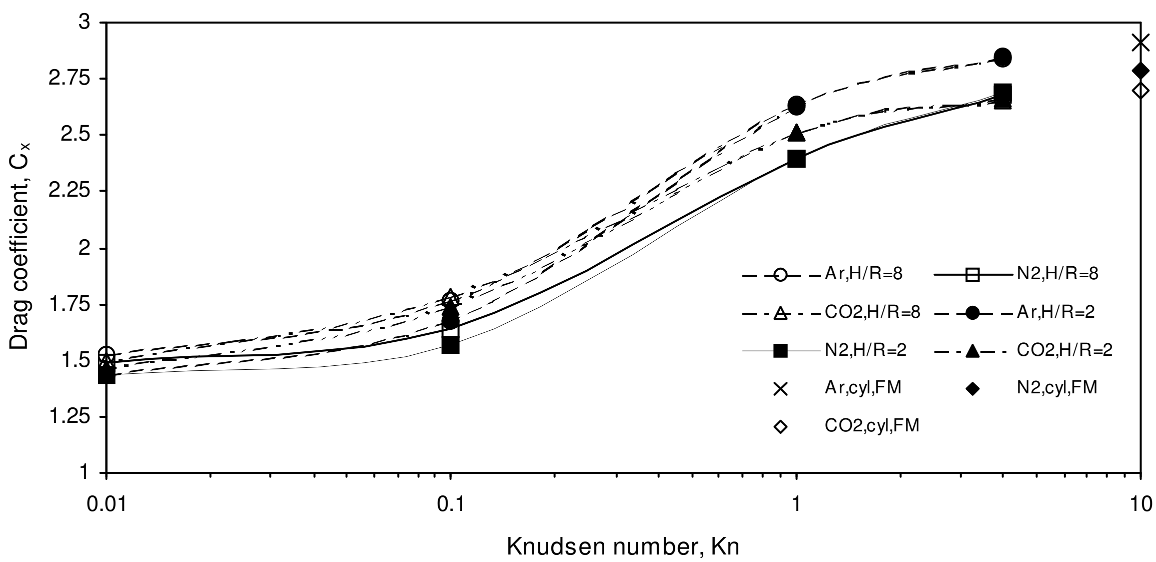


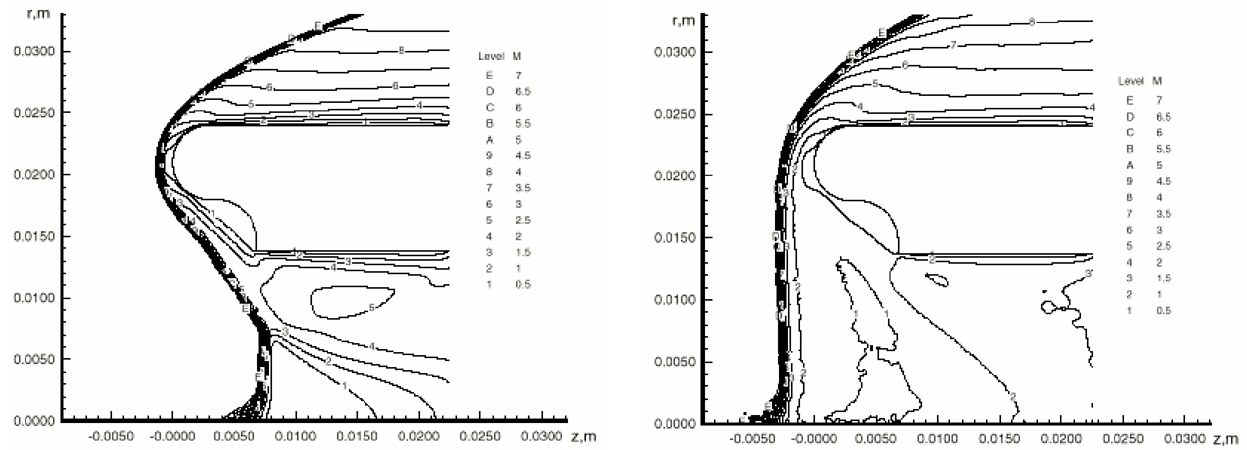
FIGURE 8. Drag coefficient C_x of a torus vs. Knudsen number $Kn_{\infty,D}$ and various geometrical factors *H/R* in the flows of argon, nitrogen, and carbon dioxide at $M_\infty = 10$.

The influence of a ratio of the specific heats γ on drag of a torus is moderate for supersonic transition rarefied-flow regimes (Fig. 8). The drag coefficient is more sensitive to the parameter γ in near-free-molecule flow regimes [about 10%] (see also Ref. 18).

AERODYNAMICS OF TOROIDAL BALLUTE MODELS

The hypersonic flows of oxygen near a toroidal ballute model [19] have been investigated numerically with the DSMC technique [3, 15] under transitional rarefied conditions (Knudsen numbers $Kn_{\infty,D}$ from 0.005 to 1).

The effect of dissociation on chocking of ducted flows has been studied numerically for a ballute model with varying area ratio H/H_*. The present study confirms the hypothesis [19] that the flow of dissociating gas (oxygen) (Fig. 9a) is not choked at the "designed" toroid [19] with a throat radius $H_* = 0.014$ m, but the flow of perfect gas (Fig. 9b) is choked at the similar conditions. The following parameters were used in calculations: $Kn_{\infty,D} = 0.005$, $R = 0.003$ m, $U_\infty = 5693$ m/s, $p_\infty = 1.28$ kPa, and $T_\infty = 1415$ K.



(a) dissociating oxygen flow **(b) perfect-oxygen flow**

FIGURE 9. Mach number contours in oxygen flow about a toroidal ballute model at $Kn_{\infty,D} = 0.005$.

CONCLUSIONS

The hypersonic rarefied-gas flow about a torus has been studied by the direct simulation Monte-Carlo technique. The flow pattern and shock-wave shapes are significantly different for small and large inner-outer-radii ratios. At a value of the geometrical ratio parameter $H/R = 8$, the conical shock waves interact in the vicinity of the symmetry axis, creating the normal shock wave (the "Mach disk"). The reflected conical wave has different pattern of the interaction with the supersonic flow behind a torus in continuum and rarefied-gas flow regimes.

At the small ratio parameters, the front shock-wave shape becomes normal, and the front stagnation points relocate from the torus front zone towards the throat area. This phenomenon effects the drag, pressure and skin-friction distributions along the torus.

The flow patterns near torus and ballute are different for small and large inner-outer-radii ratios. At $H/R = 2$, the front shock-wave shape becomes normal, and the front stagnation points relocate towards the throat area. This phenomenon effects the drag, pressure and skin-friction distributions along the toroid. The present numerical study confirms the hypothesis [19] that the flow of dissociating gas (oxygen) is not choked near the "designed" toroidal ballute model, but the flow of perfect gas is choked at the similar conditions.

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