Aerodynamics of Two Interfering Simple-Shape Bodies in Hypersonic Rarefied-Gas Flows

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Abstract. Hypersonic rarefied-gas flows near two side-by-side plates and cylinders, a plate and cylinder over a plane surface, and a plate behind a cylinder in argon and nitrogen have been studied numerically using the direct simulation Monte-Carlo technique under the transition rarefied-gas-flow regime conditions at Knudsen numbers from 0.004 to 10. Strong influences of the geometrical factor (the ratio of a distance between bodies to a body length) and the Knudsen number on the flow structure about the bodies (the shape of shock waves, the configuration of subsonic flow zones) and on skin friction, pressure distribution, lift and drag have been found.

INTRODUCTION

Experimental and numerical studies [1-4] of aerodynamics of simple shape bodies have provided valuable information related to physics of hypersonic flows about spacecraft elements and testing devices. Numerous results had been found in the cases of plates, wedges, cones, disks, spheres, torus, and cylinders (see Refs. 1-7). The interference effect for flat strips and cylinder grids was experimentally studied by Coudeville *et al* [8] for transition rarefied-gas flows. Supersonic, subsonic, and pressure-driven, low-speed flows in two-dimensional microchannels of varying aspect ratios, $20 \geq L/2H \geq 2.5$, were studied with the DSMC technique by Mavriplis *et al* [9] and Oh *et al* [10] for a range of continuum to transitional rarefied-gas flow regimes. The results [9,10] were in qualitative agreement with other computational and experimental results for longer microchannels. Near the continuum limit, they show the same trends as classical theories [9], such as Fanno/Rayleigh flow and boundary-layer interaction with shocks.

In the present study, the hypersonic rarefied-gas flow about two side-by-side plates of varying small aspect ratios, $2 \geq L/2H \geq 0.4$, has been studied at Knudsen numbers $Kn_{\infty,L}$ from 0.024 to 1.8. The flow pattern for such a configuration has not been discussed in the research literature. Numerical results have been obtained using the direct simulation Monte Carlo (DSMC) technique [2] and the computer code [11] developed by Graeme Bird. Several features of the flow are unique. For example, if the distance between the plates, $2H$, is significantly larger the plate length L, than the flow can be approximated by a stream between two isolated plates [2-6]. At $H \leq 0.25L$, the rarefied gas flow has some features of a stream near a bluff body [12]. In the first case, two oblique shock waves interact in the vicinity of the symmetry plane generating the normal shock wave and the Mach reflected waves far behind the bodies. In the second case, the front shock wave would be normal and the pressure and skin-friction distributions along the upper and bottom surfaces would be difficult to predict. At $H \leq 0.5L$, the flow pattern and shock-wave shapes are very complex. Therefore, simple approximations should not be used to define the aerodynamics of side-by-side bodies.

Flow about two side-by-side cylinders, their aerodynamic characteristics, and interference between cylinder and a plane surface have also been studied under the conditions of a hypersonic rarefied-gas stream at Knudsen numbers $Kn_{\infty,R}$ from 0.0167 to 10 and a range of geometrical factors ($6R \geq H \geq 2R$). For $3R \geq H$, the repulsive lift force has been found to become significant with a lift-drag ratio of 0.35. Blevins [12] previously analyzed the continuum streams.

Finally, the rarefied-nitrogen flow about a blunt plate located in the wake of a cylindrical wire has been numerically studied. Hayes and Probstein [13], Oguchi [14], and Allegre and Bisch [15] showed that the skin friction and pressure coefficients are maximal near the leading edge of the plate. Bisch [16] offered a unique experimental technique of the friction reduction by adding a wire-shaped “fore-leading edge” in front of the plate. The identical study of continuum flow regimes was made by Yegorov *et al* [17]. It was found that the induced wake flow in front of the plate reduced the strength of the shock wave and resulted in reducing the plate drag and friction.

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DSMC METHOD

The DSMC method [2] and the two-dimensional DS2G code [11] have been used in this study as a numerical simulation technique for low-density hypersonic gas flows. Molecular collisions in argon and nitrogen are modeled using the variable hard sphere molecular model [2]. The gas-surface interactions are assumed to be fully diffusive with full moment and energy accommodation, and the wall temperature is equal to the stagnation temperature.

Code validation was established [4,18] by comparing numerical results with experimental data [3,4]. The methodology from Refs. 2, 9 and 11 has been applied in computations. The cases that had been considered by Mavriplis *et al* [9] for airflows in near-continuum, transitional and near-free-molecular regimes were reproduced in this study.

The mesh size and the number of molecules per cell were varied until independence of the flow profiles and aerodynamic characteristics from these parameters was achieved for each case [18]. The similar mesh parameters have been used in the case of two side-by-side 0.01 m · 0.001 m plates. As an example, for calculations at H/L = 1.25, the total number of uniform cells near a plate (a half-space of the flow segment between side-by-side plates) is 12,700, the argon molecules are distributed evenly, and a total number of 139,720 molecules corresponds to an average 11 molecules per cell. 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 falls below five (see also Refs. 2 and 11). The cell geometry has been chosen to minimize the changes in the macroscopic properties across the individual cell [11]. The location of the external boundary with the upstream flow conditions varies from 0.75L to 1.5L.

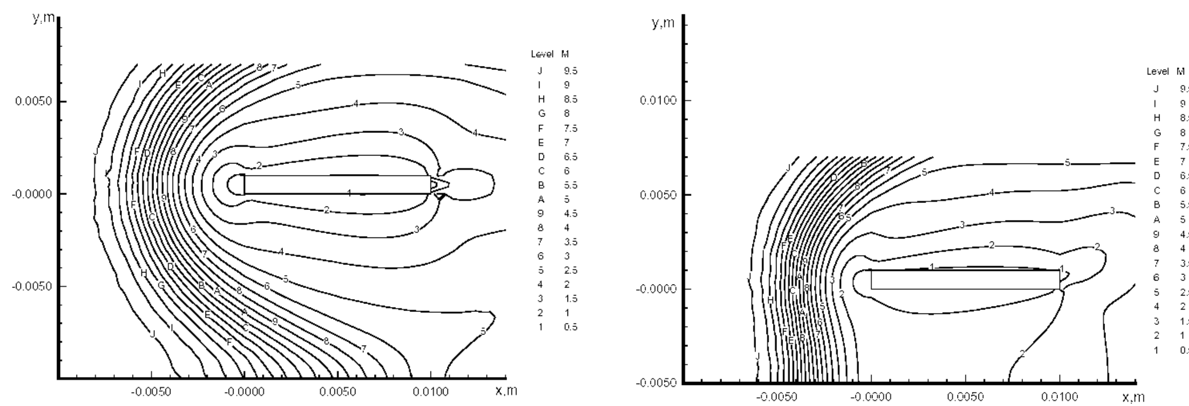
The total number of non-uniform cells [19] near a cylinder (a half-space of the flow segment between side-by-side plates for calculations at H/R = 3) is 2100, and 32,200 molecules are distributed evenly (an average 15 molecules per cell). The location of the external boundary varies from 2.5R to 4.5R.

In all cases the usual criterion [2] for the time step Δt_m has been realized, $1\times10^{-8} \leq \Delta t_m \leq 1\times10^{-6}$ s. Under these conditions, aerodynamic coefficients and gas-dynamic parameters have become insensitive to the time step. The ratios of the mean separation between collision partners to the local mean free path and the ratio of the time step to the local mean collision time have been well under unity over the flowfield [18,19].

The DS2G program [11] employs time averaging for steady flows. About 200,000 samples have been studied in the considered cases. Calculations were carried out on a personal computer with a Pentium® III 850-MHz processor. The computing time of each variant was estimated to be approximately 4 - 60 h.

INTERFERENCE OF TWO SIDE-BY-SIDE PLATES

The flow pattern over two side-by-side plates is sensitive to the major geometrical similarity parameter, H/L. The influence of this factor on the stream structure has been studied for hypersonic flow of argon at M_∞ = 10 and $Kn_{\infty,L}$ = 0.024. The flow pattern and shock-wave shapes are significantly different for large and small geometric ratios.

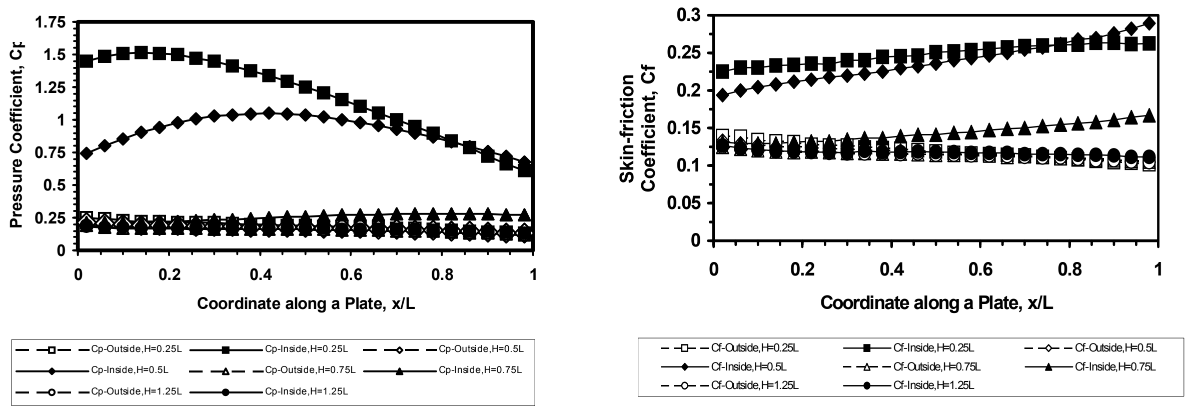


a) ***H* = *L*** **b)** ***H* = 0.5*L***

FIGURE 1. Mach number contours in argon flow about a side-by-side plate at $Kn_{\infty,L}$ = 0.024 and various H/L-ratios.

At H/L = 1.0, a strong oblique shock wave can be observed near the plate (see Fig. 1a). Two oblique shock waves interfere near the symmetry plane. The subsonic and supersonic areas (at M ≤ 2.5) of the flow near the plates are symmetrical, which indicates that there is no lift force acting on the plates for the specified conditions. At H/L = 0.5, the flow near a plate becomes significantly asymmetrical, the disturbances interact in the vicinity of the symmetry plane, creating the Mach normal shock wave and a wide subsonic area, which occupies the whole "throat" area between two side-by-side plates (see Fig. 1b). The latter effect plays a fundamental role in the redistribution of pressure and skin friction along the plate surface (Figs. 2a and 2b, respectively). This phenomenon produces significant repulsive lift force. A non-monotonous dependency of lift and drag from values of the Knudsen number has been found for various geometric factors (see Fig. 3). The drag approaches the free-molecular limit [20] at $Kn_{\infty,L} > 2$.

The rarefaction effects on the lift force are significant at all considered values of the geometrical factor ($1.25 \geq H/L \geq 0.25$). At small factors, the repulsive lift force on side-by-side plates becomes significant with the lift-drag ratio of 1.6 in near-continuum flow regime and essentialy reduces (up to 0.4) in the near-free-molecular flow.



a) Pressure Coefficient **b) Skin-friction Coefficient**

FIGURE 2. Pressure and Skin-friction Coefficients along the Side-by-Side Plate at $Kn_{\infty,L} = 0.024$ at $M_\infty = 10$.

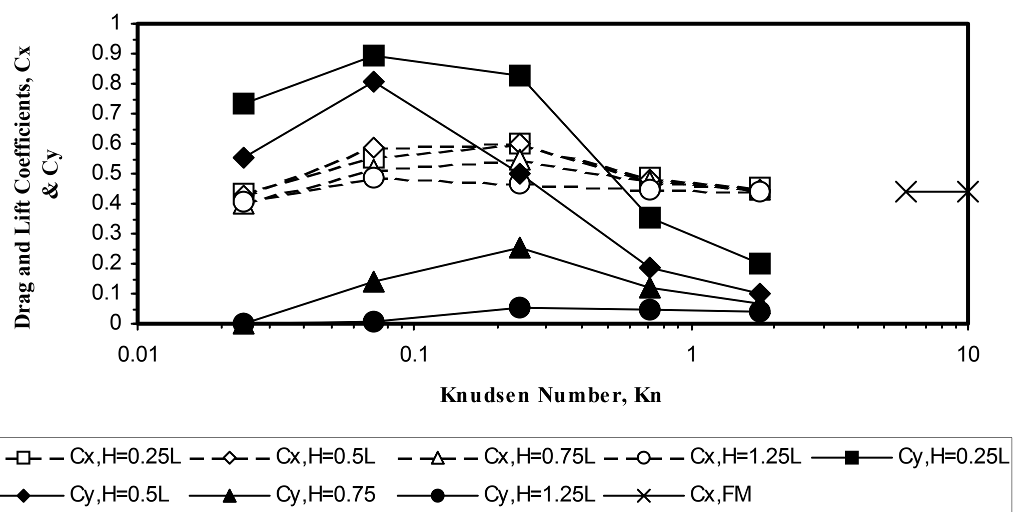
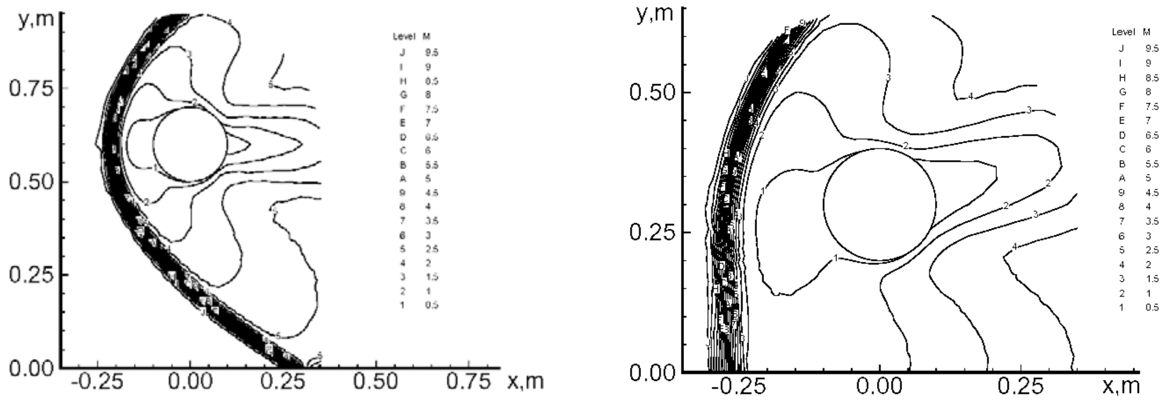


FIGURE 3. Total Drag and Lift Coefficients of the Side-by-Side Plates vs. Knudsen Number $Kn_{\infty,L}$ at $M_\infty = 10$.

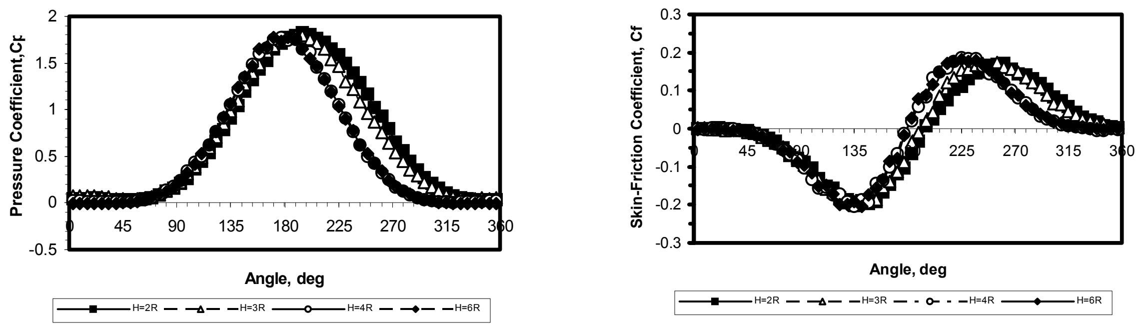
AERODYNAMICS OF TWO SIDE-BY-SIDE CYLINDERS

The flow pattern over two side-by-side cylinders is also sensitive to the major geometrical similarity parameter, H/R (see Figs. 4a and 4b). The influence of this parameter on the flow structure has been studied for hypersonic flow of argon at $M_\infty = 10$ and $Kn_{\infty,R} = 0.1$. At the small ratio parameters, $H/R \leq 2$, the front shock-wave shape becomes normal (see Fig. 4b), and front stagnation points (180°) relocate from the cylinder front zone towards the "throat" area (see Figs. 5a and 5b). This phenomenon[4] effects the drag, pressure and skin-friction distributions along a cylinder and produces significant repulsive lift force (see Fig. 6) with $C_y/C_x = 0.35$. The geometrical factor becomes insignificant on the drag both under continuum flow regime conditions and in free-molecule flow at $H/R \geq 4$.



a) $H = 6R$ **b)** $H = 2R$

FIGURE 4. Mach Number Contours in Argon Flow about a Side-by-Side Cylinder at $Kn_{\infty,R}$ =0.1 and Various H/R-ratios.



a) Pressure Coefficient **b)** Skin-friction Coefficient

FIGURE 5. Pressure and Skin-friction Coefficients along the Side-by-Side Cylinder at $Kn_{\infty,R} = 0.1$.

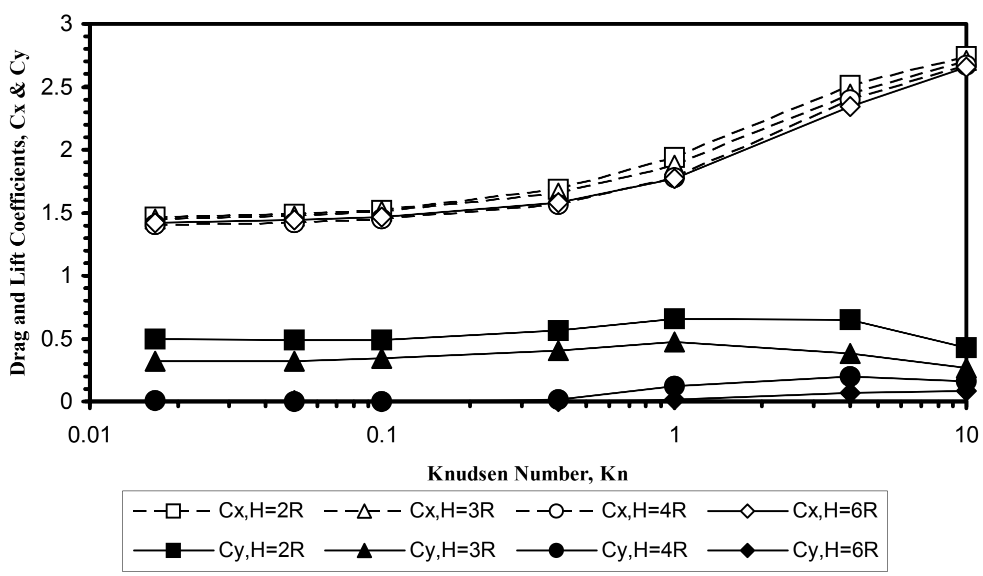
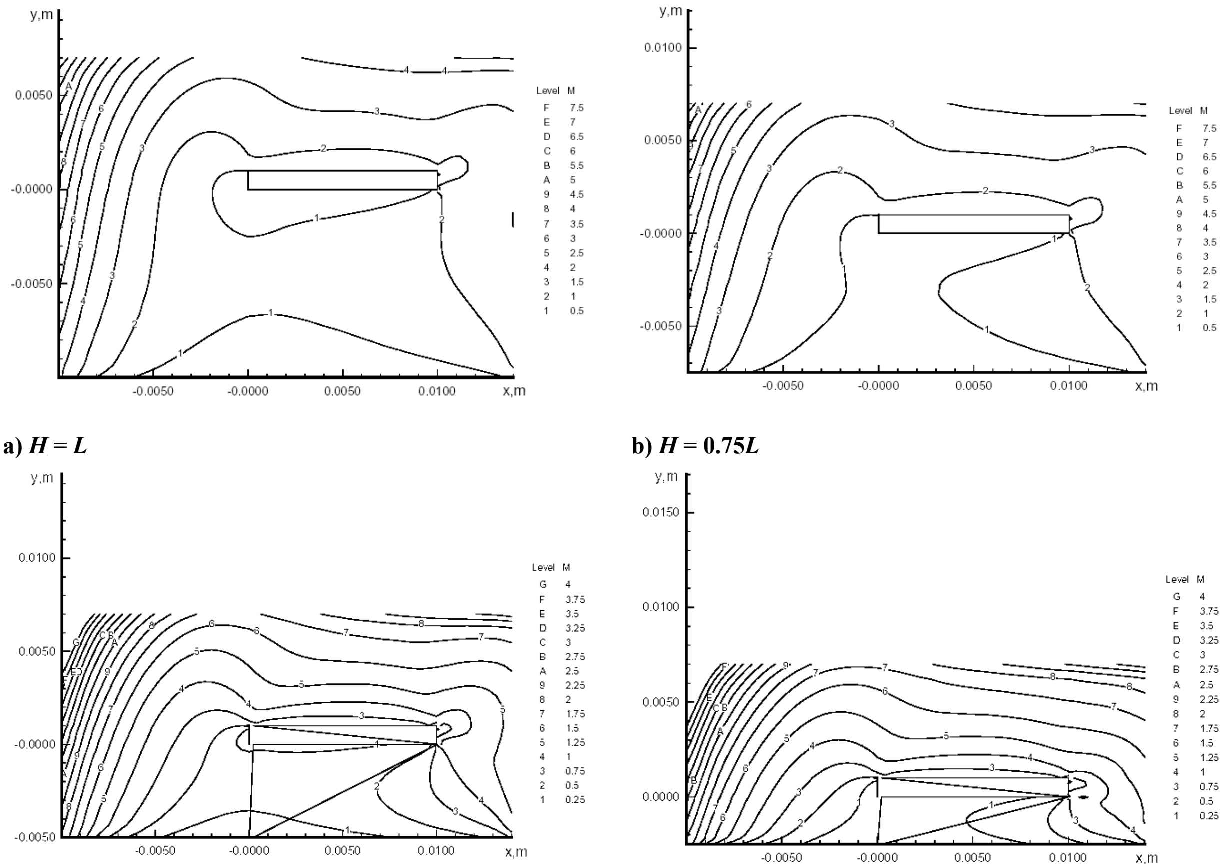


FIGURE 6. Total Drag and Lift Coefficients of the Side-by-Side Cylinder vs. Knudsen Number $Kn_{\infty,R}$ at $M_\infty = 10$.

PLATE OVER A PLANE SURFACE

In the case of a plate over a surface, the subsonic area between the plane surfaces becomes much wider than in the case of two side-by-side plates (see Figs 7a-7d). The detached shock wave interacts with the growing boundary layer above the surface. For $Kn_{\infty,L} = 0.071$ and $M_{\infty} = 10$, this effect results in a significant increase (20%) of the repulsive lift force at $2H/L \geq 1$ (see Fig. 8).



a) $H = L$ **b)** $H = 0.75L$

c) $H = 0.5L$ **d)** $H = 0.25L$

FIGURE 7. Mach Number Contours in Argon Flow about a Plate over a Plane Surface at $Kn_{\infty,L} = 0.07$ and various H/L-ratios.

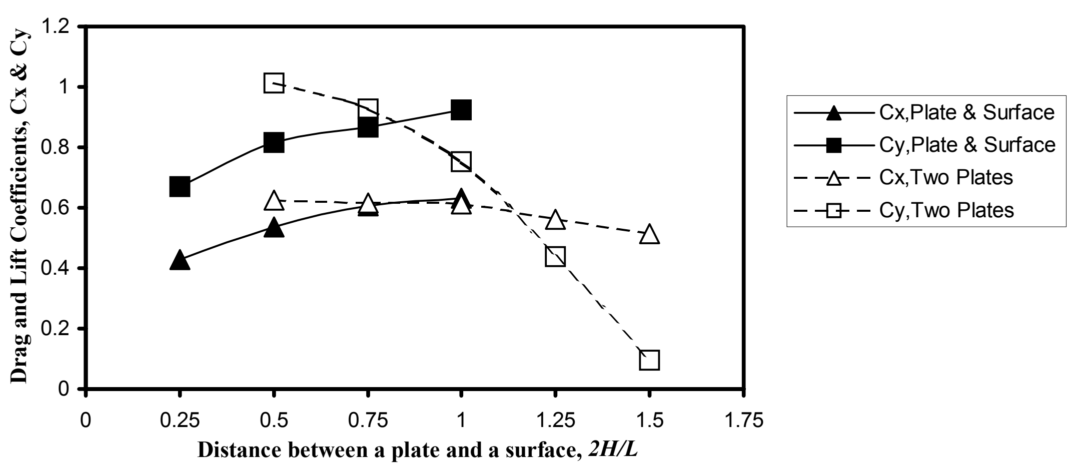
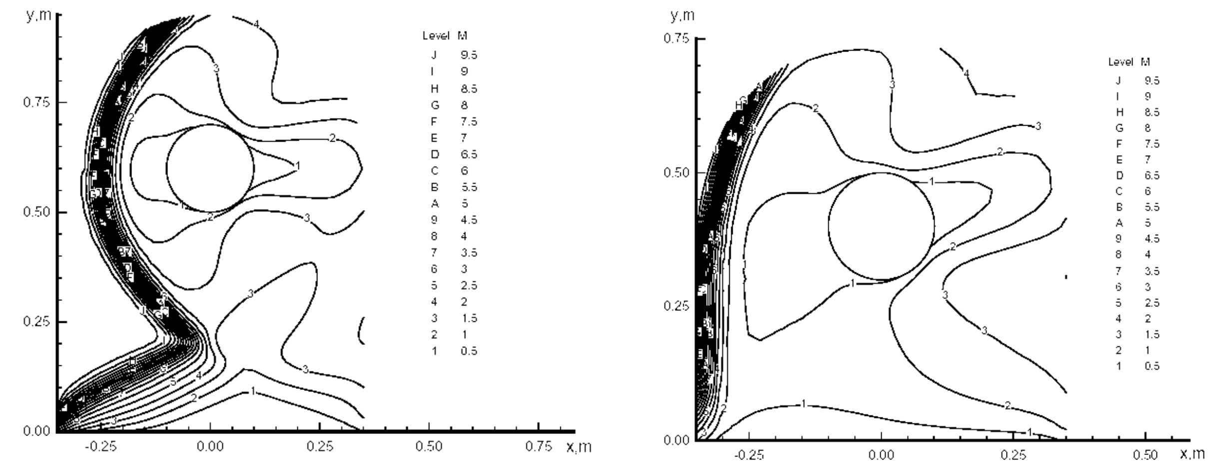


FIGURE 8. Total Drag and Lift Coefficients of a Plate over a Surface vs. Coefficients of Side-by-Side Plates.

CYLINDER OVER A PLANE SURFACE

The argon flow about a cylinder located over a plane surface has been considered at $Kn_{\infty,L}$ = 0.1 and M_{∞} = 10. At a large distance between them, $H \geq 6R$, the interference of the shock waves does not change significantly the symmetrical flow near the cylinder (see Fig. 9a), and the repulsive lift force is negligible. At the smaller ratio parameters, $H/R \leq 4$, the front shock-wave shape becomes normal (see Fig. 9b) and, as a result of interference between the shock wave and the growing boundary layer near the surface, the subsonic area about the cylinder becomes asymmetrical and much wider than in the case of two side-by-side cylinders. The latter effect results in a significant increase (more than 20%) of the repulsive lift force at $H/R \leq 4$.

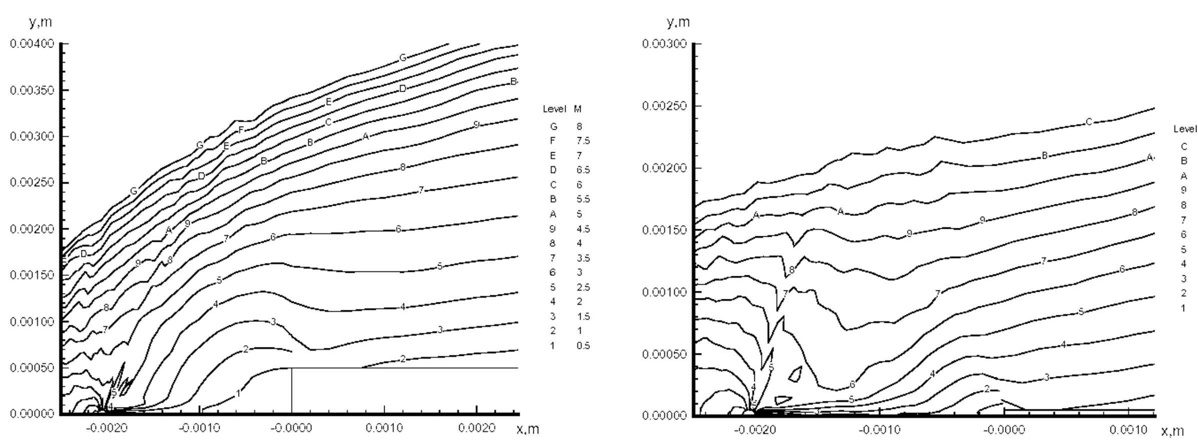


a) $H = 6R$ **b)** $H = 4R$

FIGURE 9. Mach Number Contours in Argon Flow about a Cylinder over a Plate at $Kn_{\infty,R}$ = 0.1 and Various H/R-ratios.

PLATE IN THE WAKE OF A CYLINDRICAL WIRE

In the present analysis, the major regularities in hypersonic rarefied-gas flow about a plate (L = 0.01 m) with a thickness ratio $0.01 \leq t/L \leq 0.1$ located in the wake of a circular cylinder (10^{-4} m $\leq D \leq 10^{-3}$ m) have been studied under the conditions [13-17] of the strong interaction regime. The analysis of two-dimensional nitrogen flow is made using the DSMC technique [2,11] for rarefied-gas flow regimes at Knudsen number $Kn_{\infty,L}$ = 0.004, Mach number M_{∞} = 15, stagnation temperature T_0 = 1100 K, and wall temperature T_w = 295 K.



a) D/t **= 0.1,** t/L **= 0.1,** Δ/L **= 0.2,** L **= 0.01 m** **b)** D/t **= 1,** t/L **= 0.01,** Δ/L **= 0.2,** L **= 0.01 m**

FIGURE 10. Mach number contours in nitrogen flow about a plate in the wake of a cylinder at $Kn_{\infty,L}$ = 0.004 and various D/t-ratios.

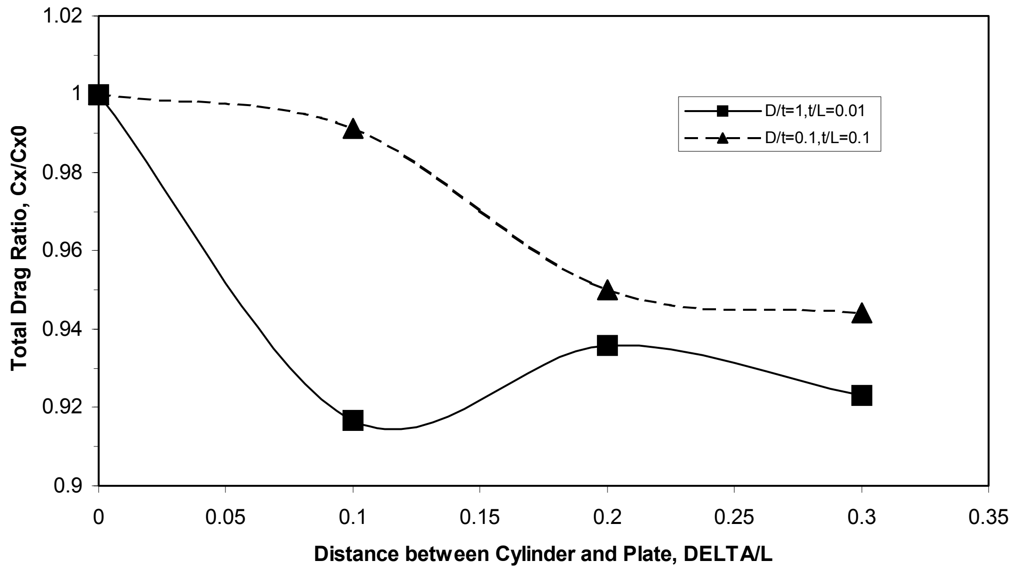


FIGURE 11. Effect of the Distance between Cylinder and Plate, Δ, on the Total Drag of the Plate.

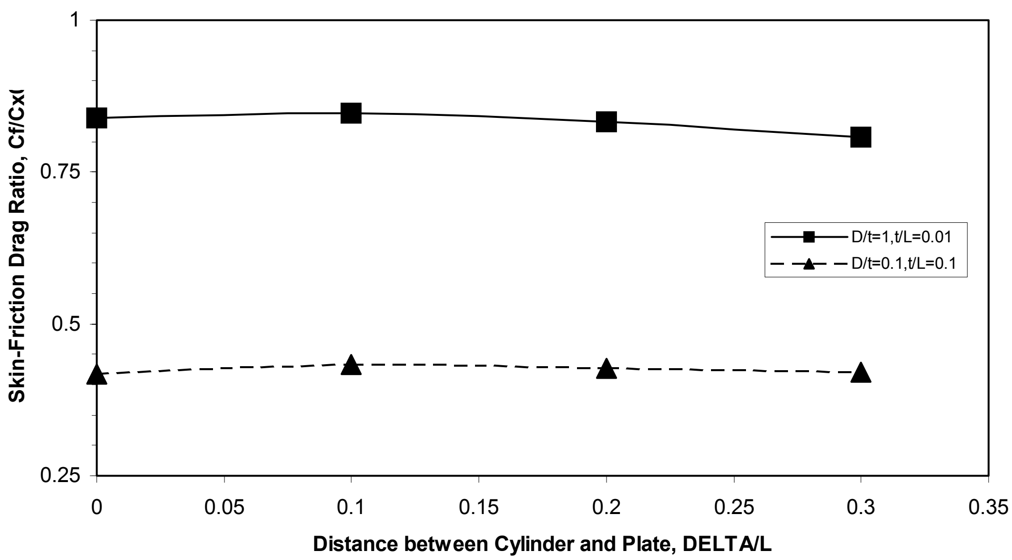


FIGURE 12. Effect of the Distance between Cylinder and Plate, Δ, on the Skin-Friction Drag of the Plate.

The influence of the geometrical factors of interference between a plate and a cylinder (i.e., the distance between the leading edge of a plate and a rear point of a cylinder, Δ, and the ratio of the cylinder diameter to the plate thickness, D/t) on flowfield characteristics, skin-friction and pressure distributions along the surfaces of the bodies, and on the drag has been studied. The location of the external boundary with the upstream flow conditions varies from $2D$ to $5D$. The wake behind the cylinder interacts with the shock wave near the leading edge of a plate. This interaction results in increasing the size of subsonic zone (see Figs. 10a and 10b) and in redistributing pressure and skin friction along the plate. The flow pattern is different for various D/t-ratios. The induced wake flow in the front area of the plate reduces the strength of the shock wave and results in reducing the plate drag up to 8.3% (see Fig. 11) and friction – up to 5% (see Fig. 12). The maximal reduction of the plate drag is observed at $D/t = 1$ and $\Delta/L = 0.1$. These findings are in the qualitative agreement with experimental data of Bisch [16].

CONCLUSIONS

The hypersonic rarefied-gas flows about two side-by-side plates and cylinders, a plate and cylinder over a plane surface, and a plate behind a cylinder in argon and nitrogen have been studied using the direct simulation Monte-Carlo technique. The flow pattern and shock-wave shapes are significantly different for small and large geometric ratios. At a value of the geometrical ratio parameter *H/L* of 0.5, the disturbances interact in the vicinity of the symmetry plane, creating a normal shock wave and a wide subsonic area, which occupies the whole "throat" area between the plates. This phenomenon affects the drag, pressure and skin-friction distributions along the plates, and produces significant repulsive lift force. A non-monotonic dependency of lift, drag and lift-drag ratio versus Knudsen number has been found for different geometric factors. The rarefaction effects on the lift force are significant at all considered values of the geometric factor ($1.25 \geq H/L \geq 0.25$), and they are responsible for non-monotonic dependency of the lift force and lift-drag ratio with the maximum value of 1.7.

The similar effects have been found in the case of hypersonic argon flow about two side-by-side cylinders. At the small ratio parameters, $H/R \leq 3$, the front shock-wave shape becomes normal, a wide subsonic area occupies the whole "throat" area between the cylinders, and the front stagnation points relocate from the cylinder front zone to the throat area. This phenomenon affects the drag, pressure and skin-friction distributions along the cylinders, and produces significant repulsive lift force with the lift-drag ratio of 0.35.

The subsonic area between the plate and a plane surface becomes much wider than in the case of two side-by-side plates. This effect results in the significant increase (more than 20%) in the repulsive lift force at $2H/L \geq 1$.

In the case of a blunt plate located in the wake of a cylindrical wire, the induced wake flow in front of the plate reduces the strength of the shock wave and results in reducing the plate drag up to 8.3%. The considered examples demonstrate the importance of studying the interference effects in applied hypersonic aerodynamics.

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