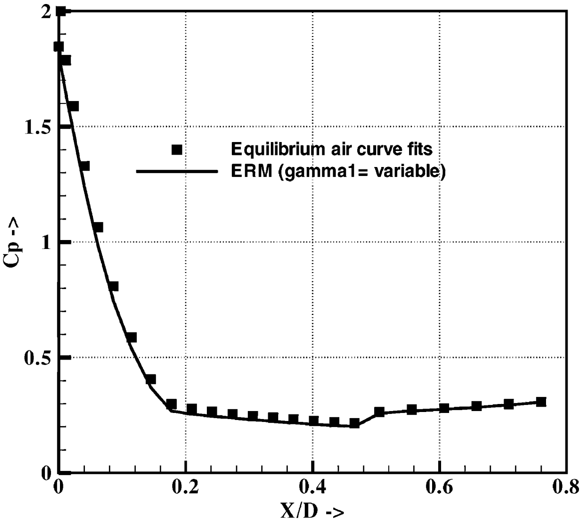


Fig. 4 Surface-pressure distribution on reentry capsule at $M = 10$ and $\alpha = 0$ deg.

wind-tunnel test data.[8] The present solver is used to analyze the flow with energy relaxation method for polytropic index of 1.4, 3, and variable [i.e., the maximum value of the polytropic index is computed at each time step that satisfies the entropy condition (4)]. The computed surface pressure for polytropic index 1.4, that is, with no relaxation of energy compares well with the experimental data in the region of lower temperature. The computed pressure for the higher value of polytropic index compares well in the higher temperature regions, but its value is higher at other regions. This is because, away from the stagnation region, the temperature is lower, where the real-gas effects are less. However, the computed surface pressure is well within the error bands[8] of wind-tunnel test data.

Hypersonic Flow at Mach Number 10

The flow analysis is carried out at the flight condition for Mach number 10 with freestream pressure of 26,500 Pa and density of 0.4122 kg/m^3. This flight condition is generally adopted for the equilibrium code verification and validation. Figure 4 shows the pressure distribution on the body obtained using the energy relaxation method with variable polytropic index and the equilibrium air curve fits. Thus, the energy relaxation method yields quite accurate results.

Conclusions

The energy relaxation method together with HLLC flux splitting has been implemented for three-dimensional real-gas flow analysis over a reentry capsule. The computed pressure compares well with wind-tunnel test data for Mach number 5 and that with air curve-fit data for Mach number 10. From these results, it can be concluded that energy relaxation method together with HLLC flux splitting is an efficient and accurate approach in computing real-gas flows for industrial applications.

Acknowledgments

The authors thank P. Srinivasa for his valuable comments and E. Janardhana for providing encouragement in the work.

References

[1]Vincenti, W., and Kruger, C., *Introduction to Physical Gas Dynamics*, Wiley, New York, 1965, p. 154.

[2]Mottura, L., "An Evaluation of Roe's Scheme Generalized for Equilibrium Real Gas Flows," *Journal of Computational Physics*, Vol. 138, No. 2, 1997, pp. 354–399.

[3]Coquel, F., and Perthame, B., "Relaxation of Energy and Approximate Riemann Solvers for General Pressure Laws in Fluid Dynamics," *SIAM Journal Numerical Analysis*, Vol. 35, No. 6, 1998, pp. 2223–2249.

[4]In, A., "Numerical Evaluation of an Energy Relaxation Method for Inviscid Real Fluids," *SIAM Journal of Scientific Computing*, Vol. 21, No. 1, 1999, pp. 340–365.

[5]Philipe, M., and Shu, C. W., "Real Gas Computation Using an Energy Relaxation Method and High Order WENO Scheme," *Journal of Computational Physics*, Vol. 148, No. 1, 1999, pp. 59–81.

[6]Batten, P., Leschziner, M. A., and Goldberg, U. C., "Average State Jacobians and Implicit Method for Compressible Viscous and Turbulent Flows," *Journal of Computational Physics*, Vol. 137, No. 1, 1997, pp. 38–78.

[7]Venkatakrishnan, V., "On the Accuracy of Limiters and Convergence to Steady State Solutions," AIAA Paper 93-0880, Jan. 1993.

[8]Kalimuthu, R., "Surface Pressure Measurement Results on the SRE (biconic) Configuration at $M = 5$," Vikram Sarabhai Space Center, Internal Rept. VSSC/ATFD/TM_SRE/078/2003, Thiruvananthapuram, India, 2003.

P. Huseman
Associate Editor

Heat Transfer on a Hypersonic Sphere with Diffuse Rarefied-Gas Injection

Vladimir V. Riabov*
Rivier College, Nashua, New Hampshire 03060

Introduction

NUMERICAL and experimental studies[1–3] of aerothermodynamics of hypersonic vehicles have shown that the temperature in the spacecraft nose region can be extremely high, and the maximum value of the heat flux occurs at small values of the nose radius R and small local Knudsen numbers $Kn_{\infty,R}$ that characterize transitional flow regimes from free-molecule medium to continuum.[2–5] Mass injection can be considered as an effective way of the reduction of heat transfer to the surface in this area.[1–6]

The boundary-layer flow with gas blowing was studied by Warren,[6] Libbi and Gresci,[7] and Finley.[8] Only few studies (i.e., Pappas and Lee[9] and Moss[10]) were conducted in the cases of transitional Knudsen numbers. Moss[10] found that mass injection significantly reduces heat transfer to the surface, and when the mass injection rate equals 0.4 of the freestream mass flux the viscous layer is blown completely off the surface, and the heat transfer is zero.

The effect of injecting gaseous coolants on heat transfer in hypersonic perfect gas flow near blunt bodies was studied by Gershbein and Kolesnikov[11] and Emelianova and Pavlov[12] on the basis of the complete system of Navier–Stokes equations and by Moss,[10] Shen et al.,[13] Ankundinov,[14] Provotorov and Stepanov,[15] and Botin[16] on the basis of the thin viscous shock-layer model.[4] Provotorov and Stepanov[15] had found universal relations between the heat flux and the generalized blowing parameters. Heat transfer in the presence of hydrogen blowing and combustion was studied by Riabov and Botin[17] and Botin et al.[18]

These studies have shown that the effectiveness of coolant blowing increases with the decrease of the Knudsen number and becomes significant at $Kn_{\infty,R} < 0.02$. Heat-transfer experimental data[16] received by the method of two-layer thermal-indicator coating[19] confirm this conclusion. Other applications of the gas blowing include the divert and attitude reaction control systems[20] and a counterflow drag-reduction technique in high-speed systems.[21]

Presented as Paper 2004-1176 at the AIAA 42nd Aerospace Sciences Meeting, Reno, NV, 5–8 January 2004; received 17 March 2004; accepted for publication 15 April 2004.

*Associate Professor, Department of Computer Science and Mathematics, 420 S. Main Street. Senior Member AIAA.

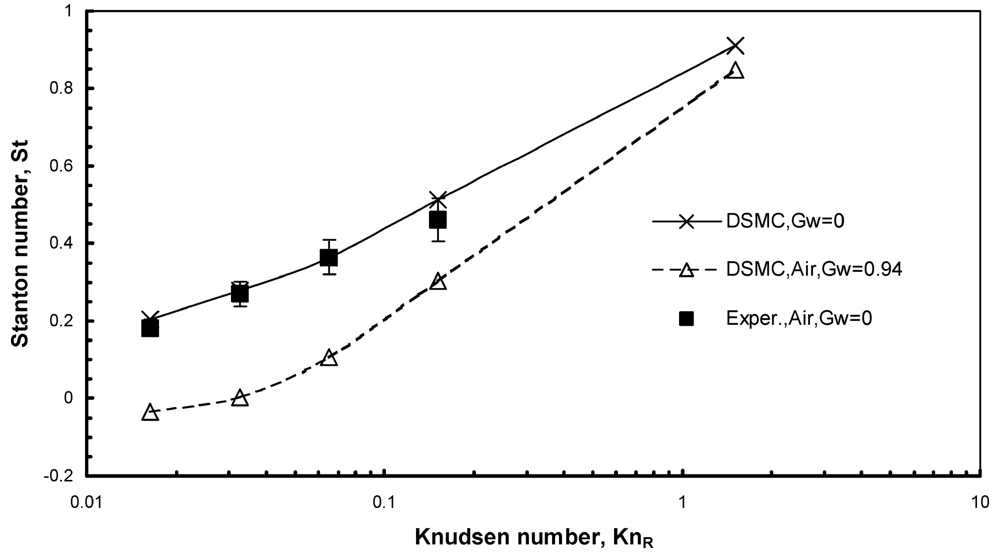
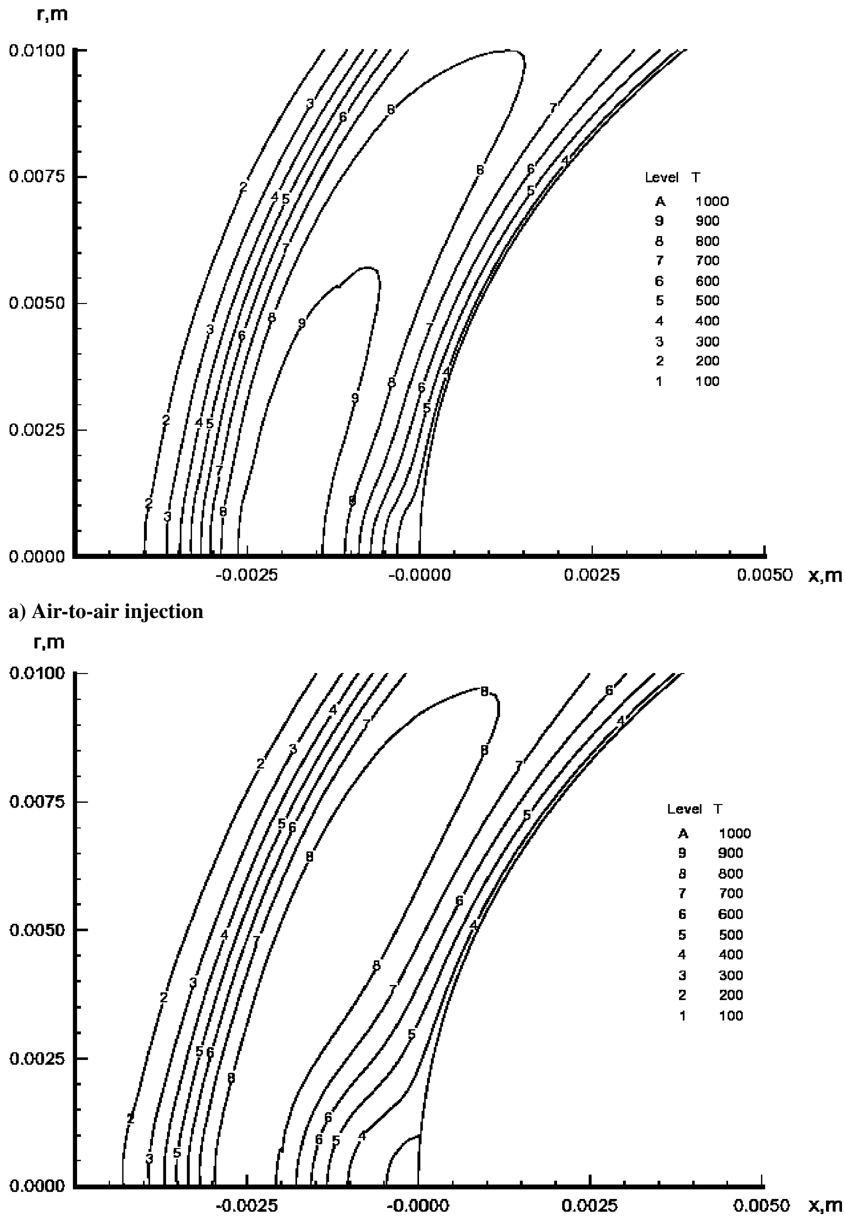


Fig. 1 Stanton number vs Knudsen number at $M_\infty = 6.5$ and $t_w = 0.31$. Experimental data are from Ref. 19.



a) Air-to-air injection

b) Helium-to-air injection

Fig. 2 Temperature contours at $Kn_{\infty,R} = 0.0163$ and mass blowing factor $G_w = 0.7$.

In the present study, the interaction of a gas flow, blowing diffusively from a nose of the sphere opposing a hypersonic freestream, is studied numerically by the direct simulation Monte Carlo (DSMC) technique[22] under the transitional rarefied-gas-flow regime conditions at Knudsen numbers $Kn_{\infty,R}$ from 0.016 to 1.5 and blowing factors G_w (the ratio of outgas mass flux to upstream mass flux) from 0.023 to 1.5. The computer code[23] was developed by Graeme Bird.

DSMC Method

The DSMC method[22] has been used in this study as a numerical simulation technique for low-density hypersonic gas flows. The DSMC/DS2G code[23] (ver. 3.2) is used for numerical calculations. Molecular collisions in air and helium are modeled using the variable-hard-sphere molecular model.[22] The gas-surface interactions are assumed to be fully diffusive with full moment and energy accommodation. The code validation was tested by the author[24,25] in comparing numerical results with experimental data[19,24,25] related to the simple-shape bodies. As an example, the comparison of the DSMC recent numerical results with experimental data[19] in air (without blowing) is shown in Fig. 1 for a wide range of Knudsen numbers from 0.016–1.5 and flow parameters: Mach number $M_\infty = 6.5$ and temperature factor $t_w = 0.31$. The error of experimental data[19] (error bars in Fig. 1) was estimated as 8–12% at different flow regimes (see Refs. 16 and 19 for details). The numerical results correlate well with experimental data at $0.016 < Kn_{\infty,R} < 0.15$.

The methodology from Refs. 22 and 23 has been applied in computations. The cases that had been considered by Bird[23] for airflow in transitional regimes were reproduced in this study. The mesh size and number of molecules per cell were varied until independence of the flow profiles and aerothermodynamic characteristics from these parameters was achieved for each considered case. In calculations at conditions just mentioned, the total number of cells near a sphere (a half-space of the flow segment) is 4200; the molecules are distributed unevenly; and a total number of 129,500 molecules corresponds to an average 31 molecules per cell. Following the recommendations of Refs. 22 and 23, acceptable results are obtained for an average of at least 10 molecules per cell in the most critical region of the flow. The error was pronounced when this number falls below five. The cell geometry has been chosen to minimize the changes in the microscopic properties (pressure, density, and temperature) across the individual cell.[22] The variation in cell width has been based on the geometric progression principle[22] and defined by the ratio $c = 20$ of the width of the cell adjacent to outer boundary to the width of the cell adjacent to inner boundary. The location of the external boundary with the upstream flow conditions varies from $0.75R$ to $1.5R$.

The DS2S program employed time averaging for steady flows.[23] About 95,000 samples have been studied in the considered cases. In

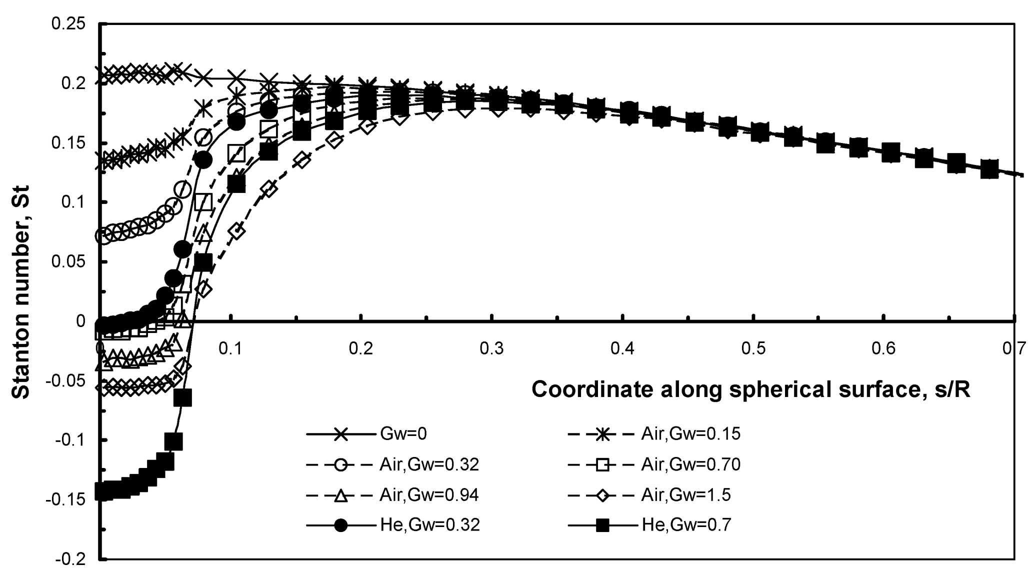


Fig. 3 Stanton number along the spherical surface at $Kn_{\infty,R} = 0.0163$ and various air-to-air and helium-to-air mass blowing factors.

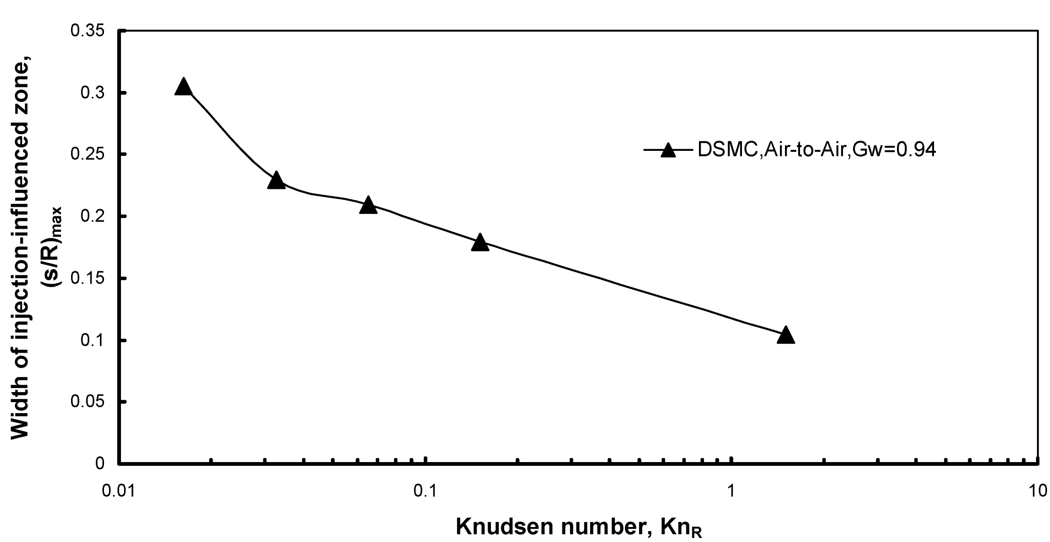


Fig. 4 Width of the injection-influenced zone $(s/R)_{max}$ vs Knudsen number at $G_w = 0.94$.

all cases the usual criterion[22] for the time step Δt_m has been realized, $2 \times 10^{-8} \leq \Delta t_m \leq 1 \times 10^{-6}$ s. Under these conditions, aerothermodynamic coefficients and gasdynamic 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 collision time ratio[23] of the time step to the local mean collision time have been well under unity over the flowfield.

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 12–80 h.

Results

Influence of the Air Blowing Factor G_w

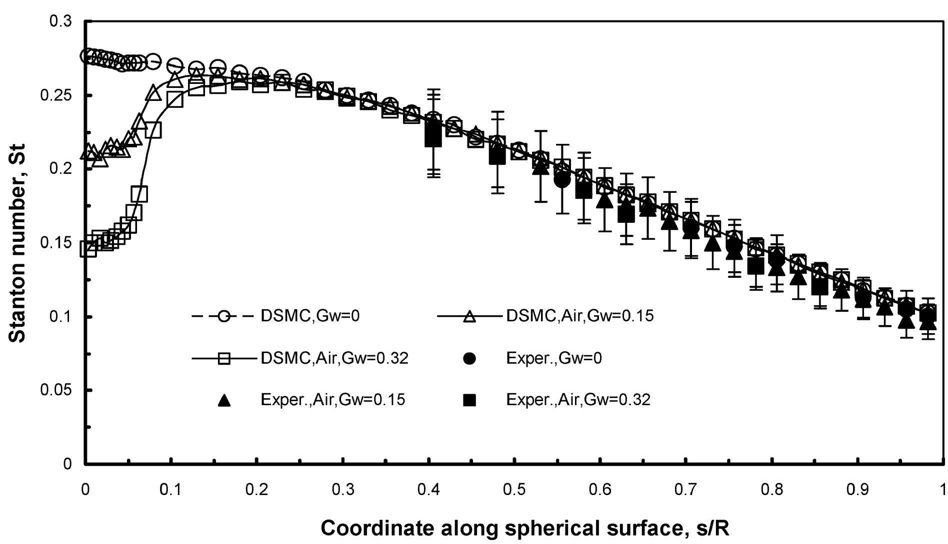
The flow pattern over sphere is significantly sensitive to the blowing parameter G_w, which is the ratio of counterflow outgas mass flux to upstream mass flux. The influence of this parameter on the flow structure has been studied for hypersonic flow of air at $M_\infty = 6.5$ and $Kn_{\infty,R} = 0.0163$. It is assumed that the temperature factor is equal to 0.31. The flow conditions are the same as suggested by Botin[16] for experiments with air blowing in a vacuum chamber at stagnation temperature $T_0 = 1000$ K. The sphere radius is $R = 0.015$ m. Air is blowing diffusively from the orifice with the diameter $d = 0.002$ m, which is located in the front critical point of the sphere. The blowing factor varies from 0 to 1.5.

The temperature contours are shown in Fig. 2a for the case of the strong blowing factor ($G_w = 0.7$). The temperature field is disturbed in the vicinity of the orifice in the subsonic area of the flow behind the strong shock wave. The distributions of the Stanton number *St* along the spherical surface at various blowing factors are shown in Fig. 3. For the considered transitional flow regime conditions, when the mass-injection rate equals 0.7 of the freestream mass flux, the viscous layer is blown completely off the surface, and the heat transfer is zero.

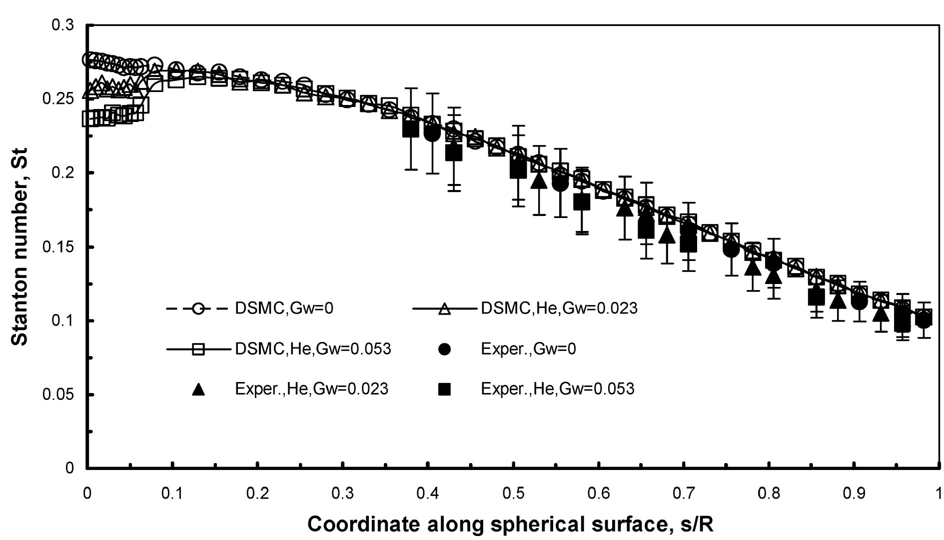
The displacement effect spreads both in the upstream direction and along the surface. The width of the displacement zone can be characterized by the normalized surface coordinate $(s/R)_{max}$, where the local heat transfer is maximum St_{max} (Fig. 3).

Influence of the Rarefaction Factor (Knudsen Number $Kn_{\infty,R}$)

The rarefaction factor, which can be characterized by the Knudsen number $Kn_{\infty,R}$, plays an important role in the flow structure[22–25] as well as in aerothermodynamics.[2,3,24,25] The Stanton number reduces significantly with decreasing the Knudsen number (see Fig. 1). The numerical data (calculated at $G_w = 0$) correlate well with experimental data[19] at $0.015 < Kn_{\infty,R} < 0.15$. The outgas counterflow reduces significantly the heat transfer to the surface. This effect is more pronounced at lower values of the Knudsen number $Kn_{\infty,R} < 0.075$ (see Fig. 1). Also the width of the injection-influenced displacement



a) Air-to-air injection



b) Helium-to-air injection

Fig. 5 Stanton number along the spherical surface at $Kn_{\infty,R} = 0.0326$ and lower mass blowing factors. Experimental data are from Ref. 16.

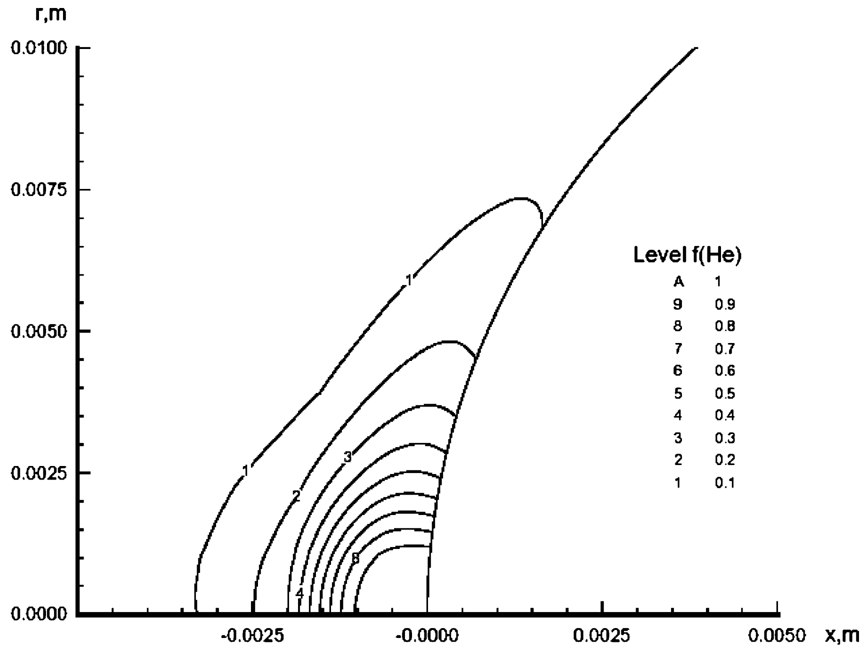


Fig. 6 Contours of helium mole fraction at $Kn_{\infty,R} = 0.0163$ and helium-to-air blowing factor $G_w = 0.7$.

zone $(s/R)_{max}$ (at $G_w = 0.94$) increases by the factor of 3 at decreasing the Knudsen number from 1.5 to 0.015 (Fig. 4).

At lower blowing factors, numerical results correlate well with experimental data of Botin,[16] which were received by the method of two-layer thermal-indicator coating[19] in a vacuum chamber at $Kn_{\infty,R} = 0.0326$ and $T_0 = 1000$ K for both the air-to-air ($G_w \leq 0.32$) and helium-to-air ($G_w \leq 0.053$) mass injections (see Figs. 5a and 5b, respectively). Under these conditions, the injection influences heat-flux distributions primarily near the orifice.

Diffuse Injection of Helium into Airstream

Helium has been selected as outgas to study the role of diffusive effects of blowing. Under transitional flow conditions ($Kn_{\infty,R} = 0.0163$), the flow structure with helium blowing has the same features as were already discussed, but the size of the displacement zone $(s/R)_{max}$ is larger than in the case of air-to-air blowing because of significant differences in diffusive properties of helium and air. The temperature contours and contours of helium mole fraction f(He) are shown in Figs. 2b and 6, respectively, for the case of the strong helium mass blowing factor ($G_w = 0.7$). The mole concentration of helium (Fig. 6) is still significant (up to the value of 0.1) at the distance of $0.2R$ in the upstream-flow direction and $3.5d$ along the sphere surface. The temperature contours (Fig. 2b) are disturbed more pronouncedly than in the case of air-to-air blowing (see Figs. 2a). Even at moderate mass-blowing factors ($0.7 > G_w > 0.32$), diffuse outgas flow displaces completely the viscous layer off the sphere surface, and values of the Stanton number become negative (see Fig. 3). The similar effect was discussed in the experimental study by Botin.[16]

Conclusions

The influence of the blowing parameter (the ratio of outgas mass flux to upstream mass flux) and the rarefaction factor (Knudsen number) on the flow structure about a sphere has been studied for hypersonic flow of air. It has been found that at transitional flow conditions ($Kn_{\infty,R} = 0.0163$), when the mass-air-injection rate equals 0.7 of the freestream mass flux, the viscous layer is blown completely off the surface, and the heat transfer is zero. The displacement effect of blowing spreads both in the counterflow direction and along the surface. This effect is more pronounced at lower values of the Knudsen number $Kn_{\infty,R} < 0.075$. The width of the injection-influenced displacement zone $(s/R)_{max}$ (at $G_w = 0.94$) increases by the factor of 3 at decreasing the Knudsen number from 1.5 to 0.016.

The temperature contours are disturbed more significantly for helium injection than in the case of air-to-air blowing. Even at moderate helium mass blowing rates ($0.7 > G_w > 0.32$), diffuse outgas flow displaces completely the viscous layer off the sphere surface.

Acknowledgments

The author expresses gratitude to G. A. Bird for the opportunity of using the DS2G computer program and to A. V. Botin for fruitful discussions.

References

[1]Gnoffo, P., "Planetary-Entry Gas Dynamics," *Annual Review of Fluid Mechanics*, Vol. 31, 1999, pp. 459–494.

[2]Koppenwallner, G., "Fundamentals of Hypersonics: Aerodynamics and Heat Transfer," *Hypersonic Aerothermodynamics*, Lecture Series, No. 1984-01, DFVLR Press, Göttingen, Germany, 1984, pp. 1–42.

[3]Gusev, V. N., "High-Altitude Aerothermodynamics," *Fluid Dynamics*, Vol. 28, No. 2, 1993, pp. 269–276.

[4]Riabov, V. V., and Provotorov, V. P., "The Structure of Multicomponent Nonequilibrium Viscous Shock Layers," AIAA Paper 94-2054, June 1994.

[5]Gusev, V. N., Provotorov, V. P., and Riabov, V. V., "Effect of Physical and Chemical Nonequilibrium on Simulation of Hypersonic Rarefied-Gas Flows," *Fluid Mechanics—Soviet Research*, Vol. 10, No. 5, 1981, pp. 123–135.

[6]Warren, C. H., "An Experimental Investigation of the Effect of Ejecting a Coolant Gas at the Nose of a Blunt Body," *Journal of Fluid Mechanics*, Vol. 8, Pt. 3, 1960, pp. 731–744.

[7]Libby, P. A., and Gresci, F. J., "Experimental Investigation of the Down-Stream Influence of Stagnation Point Mass Transfer," *Journal of Aerospace Science*, Vol. 28, No. 1, 1961, pp. 63–72.

[8]Finley, P. J., "The Flow of a Jet from a Body Opposing a Supersonic Free Stream," *Journal of Fluid Mechanics*, Vol. 26, No. 2, 1966, pp. 337–370.

[9]Pappas, C. C., and Lee, G., "Heat Transfer and Pressure on a Hypersonic Blunt Cone with Mass Addition," *AIAA Journal*, Vol. 8, No. 8, 1970, pp. 984–995.

[10]Moss, J. N., "Reacting Viscous-Shock-Layer Solutions with Multicomponent Diffusion and Mass Injection," NASA TR R-411, June 1974.

[11]Gershbein, E. A., and Kolesnikov, A. F., "Numerical Solution of the Navier–Stokes Equations in the Neighborhood of the Bluntness for Bodies in a Hypersonic Rarefied Gas Stream in the Presence of Blowing," *Aerodynamics of Hypersonic Flows with Blowing*, Moscow State Univ. Press, 1979, pp. 69–77 (in Russian).

[12]Emelianova, Z. M., and Pavlov, B. M., "Blowing from the Surface of a Sphere into a Rarefied Hypersonic Flow," *Calculation Methods and Programming*, No. 34, Moscow State Univ. Press, 1981, pp. 3–10 (in Russian).

[13] Shen, S. Y., Baron, G., and Mobley, R., "Stagnation Region Gas Injection in Low Reynolds Number Hypersonic Flow," *Proceedings of the Heat Transfer and Fluid Mechanics Institute*, Vol. 8, edited by P. A. Libby, D. B. Olfe, and C. W. Van Atta, California Univ. Press, Stanford, CA, 1967, pp. 34–57.

[14] Ankundinov, A. L., "Calculation of a Viscous Hypersonic Shock Layer with Mass Addition at Moderately Low Reynolds Numbers," *Fluid Dynamics*, Vol. 5, No. 3, 1970, pp. 40–45.

[15] Provotorov, V. P., and Stepanov, E. A., "Numerical Study of a Viscous Shock Layer in the Neighborhood of the Critical Point in the Presence of Gas Blowing," *Uchenyye Zapiski TsAGI*, Vol. 16, No. 4, 1985, pp. 44–52 (in Russian).

[16] Botin, A. V., "A Study of Local Heat Transfer to the Spherical Surface with Gas Injection at Small Reynolds Numbers," *Uchenyye Zapiski TsAGI*, Vol. 18, No. 5, 1987, pp. 41–47 (in Russian).

[17] Riabov, V. V., and Botin, A. V., "Hypersonic Hydrogen Combustion in the Thin Viscous Shock Layer," *Journal of Thermophysics and Heat Transfer*, Vol. 9, No. 2, 1995, pp. 233–239.

[18] Botin, A. V., Provotorov, V. P., and Stepanov, E. A., "Heat Transfer in the Neighborhood of the Critical Point or Line in the Presence of Hydrogen Blowing and Combustion," *Fluid Dynamics*, Vol. 30, No. 3, 1995, pp. 457–461.

[19] Ardasheva, M. M., Klimova, T. V., Pervushin, G. E., and Chernikova, L. G., "Application of a Two-Layer Thermal-Indicator Coating for Investigating Heat Transfer in Vacuum Wind Tunnels," *Uchenyye Zapiski TsAGI*, Vol. 10, No. 6, 1979, pp. 79–87 (in Russian).

[20] Gimelshein, S. F., Alexeenko, A. A., and Levin, D. A., "Modeling of the Interaction of a Side Jet with a Rarefied Atmosphere," *Journal of Spacecraft and Rockets*, Vol. 39, No. 2, 2002, pp. 168–176.

[21] Josyula, E., Pinney, M., and Blake, W. B., "Applications of a Counterflow Drag Reduction Technique in High-Speed Systems," *Journal of Spacecraft and Rockets*, Vol. 39, No. 4, 2002, pp. 605–614.

[22] Bird, G. A., *Molecular Gas Dynamics and the Direct Simulation of Gas Flows*, 1st ed., Oxford Univ. Press, Oxford, 1994, pp. 340–377.

[23] Bird, G. A., "The DS2G Program User's Guide, Version 3.2," G.A.B. Consulting Pty, Killara, Australia, 1999, pp. 1–56.

[24] Riabov, V. V., "Comparative Similarity Analysis of Hypersonic Rarefied Gas Flows near Simple-Shape Bodies," *Journal of Spacecraft and Rockets*, Vol. 35, No. 4, 1998, pp. 424–433.

[25] Riabov, V. V., "Aerodynamics of Two Side-by-Side Plates in Hypersonic Rarefied-Gas Flows," *Journal of Spacecraft and Rockets*, Vol. 39, No. 6, 2002, pp. 910–916.

A. Ketsdever
Associate Editor