wind-tunnel test data. 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 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**

9. 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 $Kn_{in,r}$ that characterize transitional flow regimes from free-molecule medium to continuum.$^{2,3}$ Mass injection can be considered as an effective way of the reduction of heat transfer to the surface in this area.$^{1-3}$

The boundary-layer flow with gas blowing was studied by Warren, Libbi and Gresci, and Finley.$^{3}$ Only few studies (i.e., Pappas and Lee$^4$ and Moss$^5$) were conducted in the cases of transitional Knudsen numbers. Moss$^5$ 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, Shen et al.,$^{13}$ Ankudinov,$^{14}$ Provotorov and Stepianov,$^5$ and Botin$^{18}$ on the basis of the thin viscous shock-layer model.$^4$ Provotorov and Stepianov$^5$ 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 $Kn_{in,r} < 0.02$. 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. Copyright © 2004 by Vladimir V. Riabov. Published by the American Institute of Aeronautics and Astronautics, Inc., with permission. Copies of this paper may be made for personal or internal use, on condition that the copier pay the $10.00 per-copy fee to the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923; include the code 0022-4650/04 $10.00 in correspondence with the CCC.

*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.

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

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 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 was developed by Graeme Bird.

DSMC Method

The DSMC method has been used in this study as a numerical simulation technique for low-density hypersonic gas flows. The DSMC/DS2G code (ver. 3.2) is used for numerical calculations. Molecular collisions in air and helium are modeled using the variable-hard-sphere molecular model. The gas-surface interactions are assumed to be fully diffusive with full moment and energy accommodation. The code validation was tested by the author in comparing numerical results with experimental data related to the simple-shape bodies. As an example, the comparison of the DSMC recent numerical results with experimental data 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 (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 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 of 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. The variation in cell width has been based on the geometric progression principle 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 0.75 $R$ to 1.5 $R$.

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

![Fig. 3](image3.png)

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](image4.png)

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

all cases the usual criterion for the time step $\Delta t_{\text{cpu}}$ has been realized, $2 \times 10^{-8} \leq \Delta t_{\text{cpu}} \leq 1 \times 10^{-6}$ s. Under these conditions, aerothermo-
dynamic coefficients and gasdynamic parameters have become insen-
tive to the time step. The ratios of the mean separation between
collision partners to the local mean free path and the collision time
ratio 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 vari-

ant 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 blow-
ing 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 Botin16
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 $(s/R)_{\text{max}}$, where
the local heat transfer is maximum $St_{\text{max}}$ (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 structure22–25 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 experi-
mental data19 at $0.015 < Kn_\infty, R < 0.15$. The outgas counterflow re-
duces 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

![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.](image-url)
zone \((s/R)_{\text{max}}\) (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,\(^6\) which were received by the method of two-layer thermal-indicator coating\(^1\) 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.

**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 \((Kn_{\infty,R} = 0.0163)\), the flow structure with helium blowing has the same features as were already discussed, but the size of the displacement zone \((s/R)_{\text{max}}\) 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 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 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**

Elements of Spacecraft Design

Charles D. Brown, Wren Software, Inc.

This new book is drawn from the author’s years of experience in spacecraft design culminating in his leadership of the Magellan Venus orbiter spacecraft design from concept through launch. The book also benefits from his years of teaching spacecraft design at University of Colorado at Boulder and as a popular home study short course.

The book presents a broad view of the complete spacecraft. The objective is to explain the thought and analysis that go into the creation of a spacecraft with a simplicity and with enough worked examples so that the reader can be self taught if necessary. After studying the book, readers should be able to design a spacecraft, to the phase A level, by themselves.

Everyone who works in or around the spacecraft industry should know this much about the entire machine.

Table of Contents:

- Introduction
- System Engineering
- Orbital Mechanics
- Propulsion
- Attitude Control
- Power System
- Thermal Control
- Command And Data System
- Telecommunication
- Structures
- Appendix A: Acronyms and Abbreviations
- Appendix B: Reference Data
- Index

AIAA Education Series
2002, 610 pages, Hardback \ ISBN: 1-56347-524-3 \ List Price: $111.95 \ AIAA Member Price: $74.95

American Institute of Aeronautics and Astronautics
Publications Customer Service, P.O. Box 960, Herndon, VA 20172-0960
Fax: 703/661-1501 \ Phone: 800/662-2422 \ E-mail: warehouse@aiaa.org
Order 24 hours a day at www.aiaa.org

AIAA