

HEAT TRANSFER ON A HYPERSONIC SPHERE WITH DIFFUSE RAREFIED-GAS INJECTION

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

Abstract

The interaction of a diffusing outgas flow from a sphere nose opposing a hypersonic free stream is studied numerically by the direct simulation Monte-Carlo technique under the transitional rarefied-gas-flow regime conditions at Knudsen numbers from 0.016 to 1.5 and blowing factors from 0.15 to 1.5. Strong influences of the blowing factor (the ratio of outgas mass flux to upstream mass flux) and the Knudsen number on the flow structure about a sphere (temperature fields, the configuration of mixing flow zones) and on heat distributions along the spherical surface have been found. At large blowing factors, the injected gas significantly reduces heat flux in wide area near the spherical nose. This effect is more pronounced for light gas (helium) injection in the near-continuum flow.

Nomenclature

- d = orifice diameter, 0.002 m
 f = mole fraction of helium
 G_w = mass injection rate ratio ("blowing" factor)
 $Kn_{\infty,R}$ = Knudsen number
 M = Mach number
 p = pressure, N/m²
 R = sphere radius, 0.015 m
 $Re_{0,R}$ = Reynolds number
 St = Stanton number
 s = coordinate along a spherical surface
 T = temperature
 t_w = temperature factor, T_w/T_0
 x = coordinate along an axis of body symmetry
- subscripts*
 R = sphere radius as a length-scale parameter
 w = wall condition
 0 = stagnation flow condition
 ∞ = freestream parameter

*Associate Professor, Department of Computer Science and Mathematics, 420 S. Main Street; vriabov@rivier.edu. Senior Member AIAA.

Introduction

Numerical and experimental studies¹⁻⁵ 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 Reynolds numbers $Re_{0,R}$.³⁻⁷ Mass injection can be considered as an effective way of the reduction of heat transfer to the surface in this area (see Refs. 1-8).

The boundary-layer flow with gas blowing was studied by Warren⁸, Libbi and Gresci⁹, and Finley¹⁰. Only few studies (i.e., Pappas and Lee¹¹ and Moss¹²) were conducted in the case of small Reynolds numbers. Moss¹² found that mass injection dramatically reduces heat transfer to the surface, and when the mass injection rate equals 0.4 of the free-stream 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 Kolesnikov¹³ and Emelianova and Pavlov¹⁴ on the basis of the complete system of Navier-Stokes equations, and by Moss¹², Shen et al.¹⁵, Ankundinov¹⁶, Provotorov and Stepanov^{17,18}, and Botin¹⁹ on the basis of the thin viscous shock layer model developed by Cheng². Provotorov and Stepanov^{17,18} had found universal relations between the relative heat flux and the generalized blowing parameters. Heat transfer in the presence of hydrogen blowing and combustion was studied by Riabov and Botin²⁰ and Botin et al.²¹

These studies have shown that the effectiveness of coolant blowing increases with the increase of the Reynolds number, and becomes significant at $Re_{0,R} > 90$. Heat transfer experimental data¹⁹ received by the method of two-layer thermal-indicator coating²² confirm this conclusion. Other applications of the gas blowing include the divert and attitude reaction control systems (see the review of Gimelshein et al.²³ and original papers²⁴⁻²⁹) and a counterflow drag reduction technique in high-speed systems (see the study of Josyula et al.³⁰ and others³¹⁻³³).

In the present study, the interaction of a blowing gas flow from a nose of the sphere opposing a hypersonic free stream is studied numerically by the

direct simulation Monte-Carlo (DSMC) technique³⁴ 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 0.15 to 1.5. Strong influences of the blowing factor and the Knudsen number on the flow structure about a sphere (temperature fields, the configuration of mixing flow zones) and on heat distributions along the surface of a sphere have been found. At large blowing factors ($G_w > 0.5$), the injected gas significantly reduces heat flux in wide area near the spherical nose. This effect is more pronounced for light gas (helium) injection in the near-continuum flow of air. The computer code³⁵ was developed by Graeme Bird.

DSMC Method

The DSMC method³⁴ has been used in this study as a numerical simulation technique for low-density hypersonic gas flows. The DSMC/DS2G code³⁵ (version 3.2) is used for numerical calculations. Molecular collisions in air and helium are modeled using the variable hard sphere (VHS) molecular model³⁴. The gas-surface interactions are assumed to be fully diffusive with full moment and energy accommodation. The code validation was tested by the author^{36,37} in comparing numerical results with experimental data^{22,36,38} related to the simple-shape bodies. As an example, the comparison of the DSMC recent numerical results with experimental data²² in air (without blowing) is shown in Fig. 1 for a wide range of Reynolds numbers from 1 to 92.8 (Knudsen numbers from 1.5 to 0.016 respectively) and flow parameters $M_\infty = 6.5$ and $t_w = 0.31$. The error of experimental data²² (error bars in Fig. 1) was estimated as 8-12% at different flow regimes (see Refs. 19 and 22 for details). The numerical results correlate well with experimental data at $10 < Re_{0,R} < 90$.

The methodology from Refs. 34 and 35 has been applied in computations. The cases that had been considered by Bird³⁵ for airflow in near-continuum 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 mentioned-above conditions, the total number of cells near a sphere (a half-space of the flow segment) is 4200 in four zones, the molecules are distributed non-evenly, and a total number of 129,500 molecules corresponds to an average 31 molecules per cell. Following the recommendations of Refs. 34 and 35, 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. The cell geometry has been chosen to

minimize the changes in the microscopic properties (pressure, density, and temperature) across the individual cell.³⁴ The variation in cell width has been based on the geometric progression principle³⁴ 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. In all cases the usual criterion³⁴ 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 (CTR parameter)³⁵ of the time step to the local mean collision time have been well under unity over the flowfield.

The DS2S program employed time averaging for steady flows.³⁵ About 95,000 samples have been studied in the considered cases. The computed results have been stored to the TECPLOT[®] files that have been further analyzed to study whether the DSMC numerical criteria³⁴ are met.

The location of the external boundary with the upstream flow conditions varies from 0.75R to 1.5R. 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 $Kn_{\infty,R} = 0.0163$ ($Re_{0,R} = 92.8$). It is assumed that the temperature factor is equal to 0.31. The flow conditions are the same as suggested by Botin¹⁹ for experiments with air blowing in a vacuum chamber (stagnation pressure $p_0 = 120$ torr and stagnation temperature $T_0 = 1000$ K). The sphere radius is 0.015 m. The diffuse outgas (air) is blowing from the orifice with the diameter of 0.002 m that is located in the critical front point of the sphere. The blowing factor varies from 0 to 1.5.

The local Mach number contours and temperature contours are shown in Figs. 2 and 3, respectively, 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. 4. For the considered near-continuum flow regime conditions, when the mass injection rate equals 0.7 of the free-stream mass flux,

the viscous layer is blown completely off the surface, and the heat transfer is zero. At stronger blowing ($G_w > 0.7$), diffuse outgas flow displaces completely the viscous layer off the sphere surface.

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 heat transfer is maximum (see Fig. 4).

Influence of the Rarefaction Factor (Reynolds Number $Re_{0,R}$)

The rarefaction factor, which can be characterized by the Reynolds number $Re_{0,R}$ (or the equivalent Knudsen number, $Kn_{\infty,R}$) plays an important role in the flow structure³⁴⁻³⁷ as well as in aerothermodynamics^{3,4,36,37}. The Stanton number reduces significantly with increasing the Reynolds number (see Fig. 1). The numerical data (calculated at $G_w = 0$) correlate well with experimental data²² at $10 < Re_{0,R} < 100$. The outgas counterflow reduces significantly the heat transfer to the surface. This effect is more pronounced at higher values of the Reynolds number, $Re_{0,R} > 20$ (see Fig. 1). Also the width of the injection-influenced “displacement” zone (at $G_w = 0.94$) increases by the factor of 3 at increasing the Reynolds number from 1 to 92.8 (see Fig. 5).

Diffuse Injection of Helium into Air Stream

Helium has been selected as outgas to study the role of diffusive effects of blowing. Under near-continuum flow conditions ($Kn_{\infty,R} = 0.0163$ or $Re_{0,R} = 92.8$), the flow structure with helium blowing has the same features as were discussed above, but the size of the “displacement” zone is larger than in the case of air-to-air blowing. The contours of helium mole fraction $f(\text{He})$, local Mach number contours and temperature contours are shown in Figs. 6, 7, and 8, respectively, for the case of the strong helium 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 upstream flow and $3.5d$ along the sphere surface. The Mach number contours (Fig. 7) are displaced and temperature contours (Fig. 8) are disturbed more pronouncedly than in the case of air-to-air blowing (see Figs. 2 and 3 respectively). Even at moderate blowing ($0.7 > G_w > 0.32$), diffuse outgas flow displaces completely the viscous layer off the sphere surface, and values of the Stanton number become negative (see Fig. 9). The similar effect was discussed in the experimental study by Botin¹⁹.

Conclusion

The influence of the blowing parameter (the ratio of outgas mass flux to upstream mass flux) and the rarefaction factor (Knudsen number or Reynolds number) on the flow structure about a sphere has been studied for hypersonic flow of air. It has been found

that at near-continuum flow regime conditions ($Re_{0,R} = 92.8$), when the mass air injection rate equals 0.7 of the free-stream 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 higher values of the Reynolds number, $Re_{0,R} > 20$ and the width of the injection-influenced “displacement” zone (at $G_w = 0.94$) increases by the factor of 3 at increasing the Reynolds number from 1 to 92.8.

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

Acknowledgments

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

References

- ¹Gnoffo, P., “Planetary-Entry Gas Dynamics,” *Annual Review of Fluid Mechanics*, Vol. 31, 1999, pp. 459-494.
- ²Cheng, H., “Perspectives on Hypersonic Viscous Flow Research,” *Annual Review of Fluid Mechanics*, Vol. 25, 1993, pp. 455-484.
- ³Koppenwallner, G., “Fundamentals of Hypersonics: Aerodynamics and Heat Transfer,” *Hypersonic Aerothermodynamics*, Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt E. V., Lecture Series, No. 1984-01, DFVLR-Press, 1984, pp. 1-42.
- ⁴Gusev, V. N., “High-Altitude Aerothermodynamics,” *Fluid Dynamics*, Vol. 28, No. 2, 1993, pp. 269-276.
- ⁵Anderson, J., *Hypersonic and High Temperature Gas Dynamics*, 1st edition, McGraw-Hill, 1989, pp. 635-645.
- ⁶Riabov, V. V., and Provotorov, V. P., “The Structure of Multicomponent Nonequilibrium Viscous Shock Layers,” Paper 94-2054, June 1994.
- ⁷Gusev, 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.
- ⁸Warren, 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. III, 1960.

- ⁹Libby, 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.
- ¹⁰Finley, 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.
- ¹¹Pappas, 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.
- ¹²Moss, J. N., "Reacting Viscous-Shock-Layer Solutions with Multicomponent Diffusion and Mass Injection," NASA TR R-411, June 1974.
- ¹³Gershbein, 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." In: *Aerodynamics of Hypersonic Flows with Blowing*, Moscow State University Press, Moscow, 1979, pp. 69-77 (in Russian).
- ¹⁴Emeliyanova, Z. M., and Pavlov, B. M., "Blowing from the Surface of a Sphere into a Rarefied Hypersonic Flow." In: *Calculation Methods and Programming*, No. 34, Moscow State University Press, Moscow, 1981, pp. 3-10 (in Russian).
- ¹⁵Shen, 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*, California University Press, Stanford, CA, 1967, pp. 34-57.
- ¹⁶Ankundinov, 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.
- ¹⁷Provotorov, 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).
- ¹⁸Provotorov, V. P., and Stepanov, E. A., "Numerical Study of Mass Exchange in the Neighborhood of the Critical Point in the Viscous Shock Layer Regime," *Trudy TsAGI*, No. 2340, 1987, pp. 70-84 (in Russian).
- ¹⁹Botin, 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).
- ²⁰Riabov, 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.
- ²¹Botin, 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.
- ²²Ardasheva, 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).
- ²³Gimelshein, 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.
- ²⁴Tartabini, P. V., Wilmoth, R. G., and Rault, D. F. G., "Direct Simulation Monte Carlo Calculation of a Jet Interaction Experiment," *Journal of Spacecraft and Rockets*, Vol. 32, No. 1, 1995, pp. 75-83.
- ²⁵Glass, C. E., and LeBeau, G. J., "Numerical Study of a Continuum Sonic Jet Interacting with a Rarefied Flow," AIAA Paper 97-2536, June 1997.
- ²⁶Kanipe, D. P., "Plume/Flowfield Jet Interaction Effects on the Space Shuttle Orbiter During Entry," AIAA Paper 82-1319, Aug. 1982.
- ²⁷Gilmore, M. R., and Warburton, K., "Axisymmetric Hypersonic Jet Interaction: a Combined Experimental and Computational Study II," AIAA Paper 95-0414, Jan. 1995.
- ²⁸Glass, C. E., "A Parametric Study of Jet Interactions with Rarefied Flows," *Proceedings of the 21st International Symposium on Rarefied Gas Dynamics*, edited by R. Brun, R. Campargue, R. Gatignol, and J.-C. Lengrand, Vol. 1, Cepadues Editions, Toulouse, France, 1998, pp. 615-622.
- ²⁹Ebrahimi, H. B., "Numerical Simulation of Transient Jet-Interaction Phenomenology in a Supersonic Free Stream," *Journal of Spacecraft and Rockets*, Vol. 37, No. 6, 2000, pp. 713-719.
- ³⁰Josyula, 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.
- ³¹Ganiev, Y. C., Gordeev, V., Krasilnikov, A., Lagutin, V., Otmenikov, V., and Panasenko, A., "Theoretical and Experimental Study of the Possibility of Reducing Aerodynamic Drag by Employing Plasma Injection," AIAA Paper 99-0603, Jan. 1999.
- ³²Shang, J., Hayes, J., Wurtzler, K., and Strang, W., "Jet-Spike Bifurcation in High-Speed Flows," *AIAA Journal*, Vol. 39, No. 6, 2001, pp. 1159-1165.
- ³³Romeo, D., and Sterrett, J., "Exploratory Investigation of the Effect of a Forward Facing Jet on the Bow Shock of a Blunt Body in a Mach Number 6 Free Stream," NASA TN D-1605, Feb. 1963.
- ³⁴Bird, G. A., *Molecular Gas Dynamics and the Direct Simulation of Gas Flows*, 1st ed., Oxford University Press, Oxford, England, UK, 1994, pp. 340-377.

³⁵Bird, G. A., "The DS2G Program User's Guide, Version 3.2," G.A.B. Consulting Pty, Killara, NSW, Australia, 1999, pp. 1-56.

³⁶Riabov, 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.

³⁷Riabov, 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.

³⁸Gusev, V. N., Erofeev, A. I., Klimova, T. V., Perepukhov, V. A., Riabov, V. V., and Tolstykh, A. I., "Theoretical and Experimental Investigations of Flow Over Simple Shape Bodies by a Hypersonic Stream of Rarefied Gas," *Trudy TsAGI*, No. 1855, 1977, pp. 3-43 (in Russian).

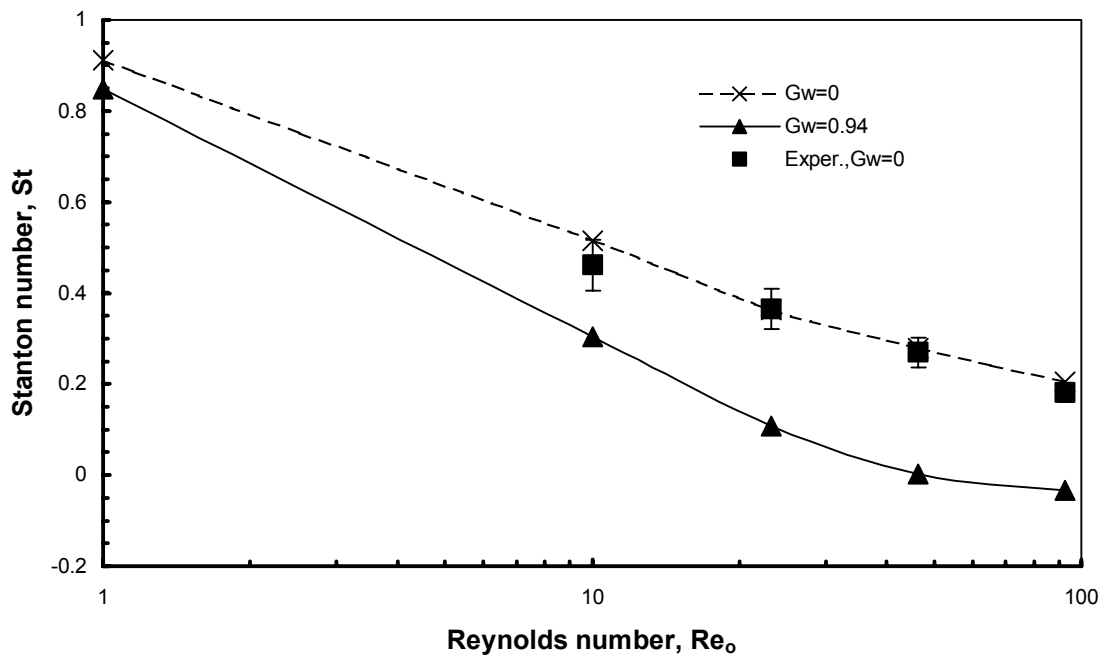


Fig. 1 Stanton number vs. Reynolds number at $M_\infty = 6.5$ and $t_w = 0.31$. Experimental data are from Ref. 22.

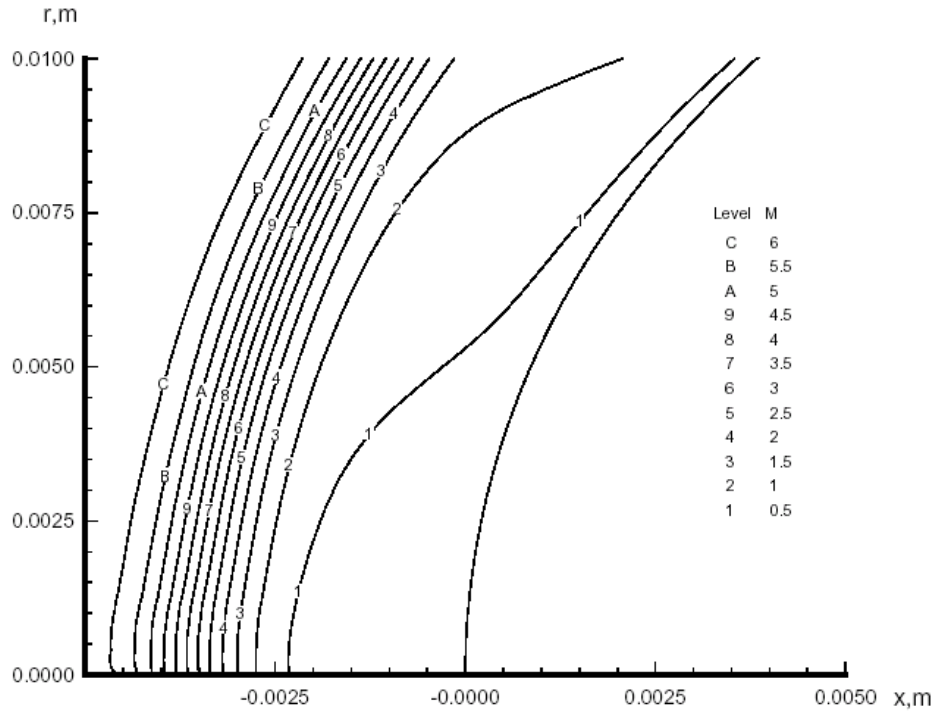


Fig. 2 Mach number contours at $Re_{\theta,R} = 92.8$ and air-to-air blowing factor $G_w = 0.7$.

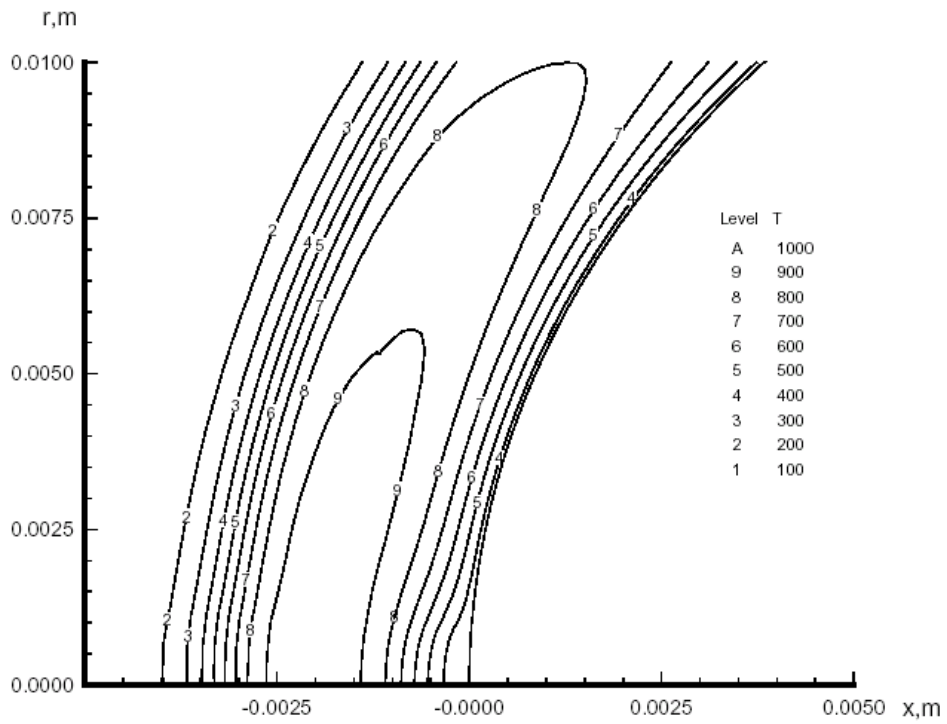


Fig. 3 Temperature contours at $Re_{\theta,R} = 92.8$ and air-to-air blowing factor $G_w = 0.7$.

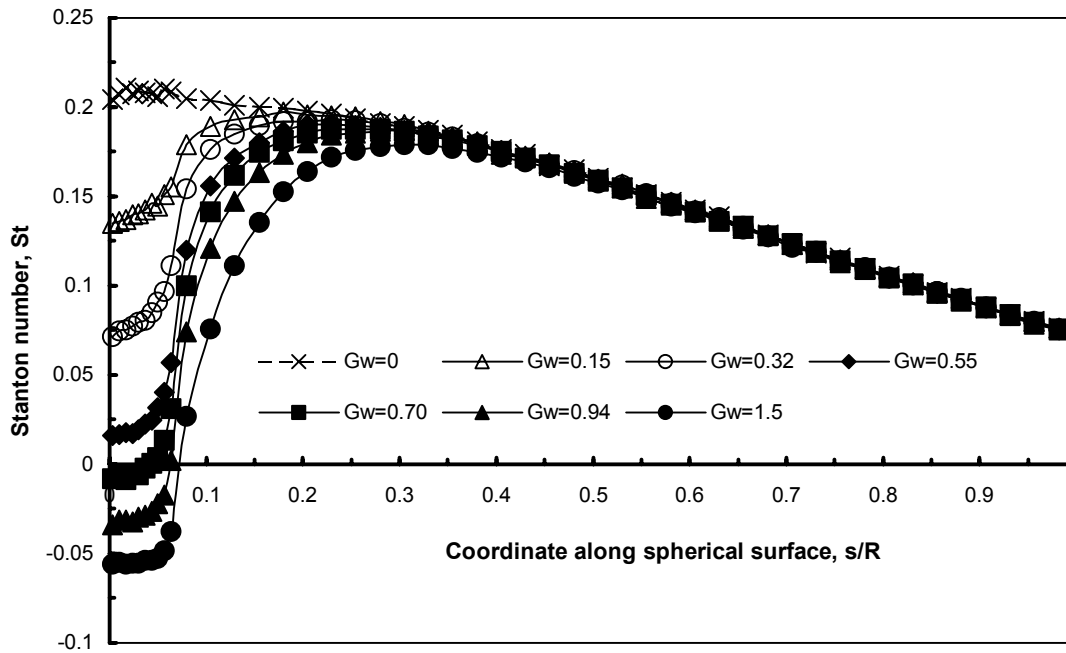


Fig. 4 Stanton number along the spherical surface at $Re_{0,R} = 92.8$ and various air-to-air blowing factors.

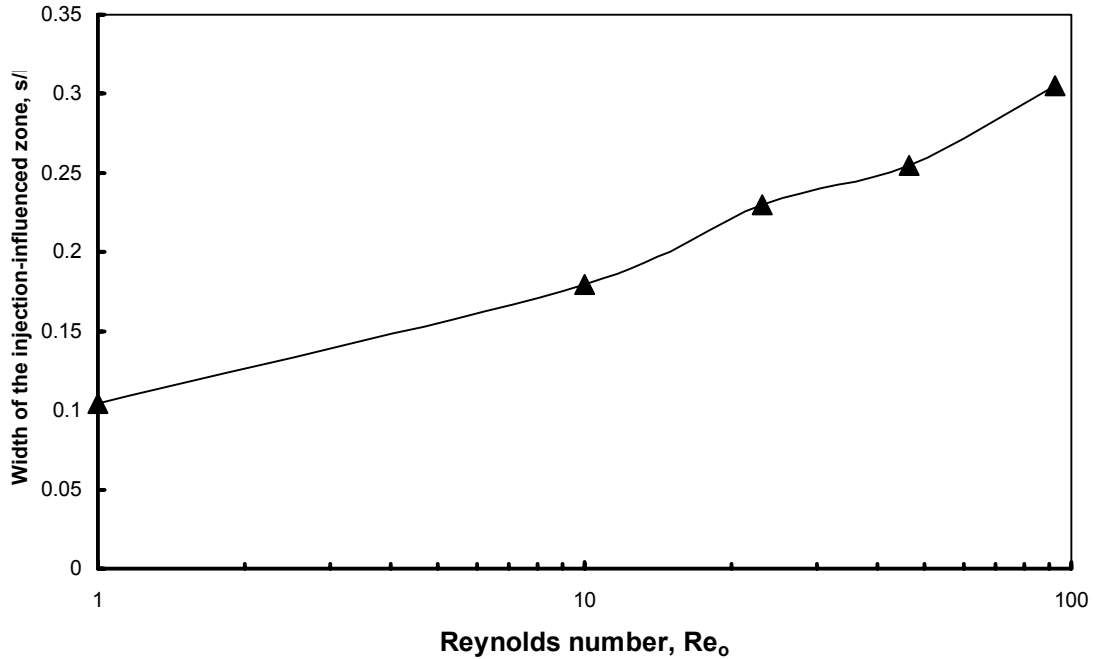


Fig. 5 Width of the injection-influenced zone vs. Reynolds number at $G_w = 0.94$.

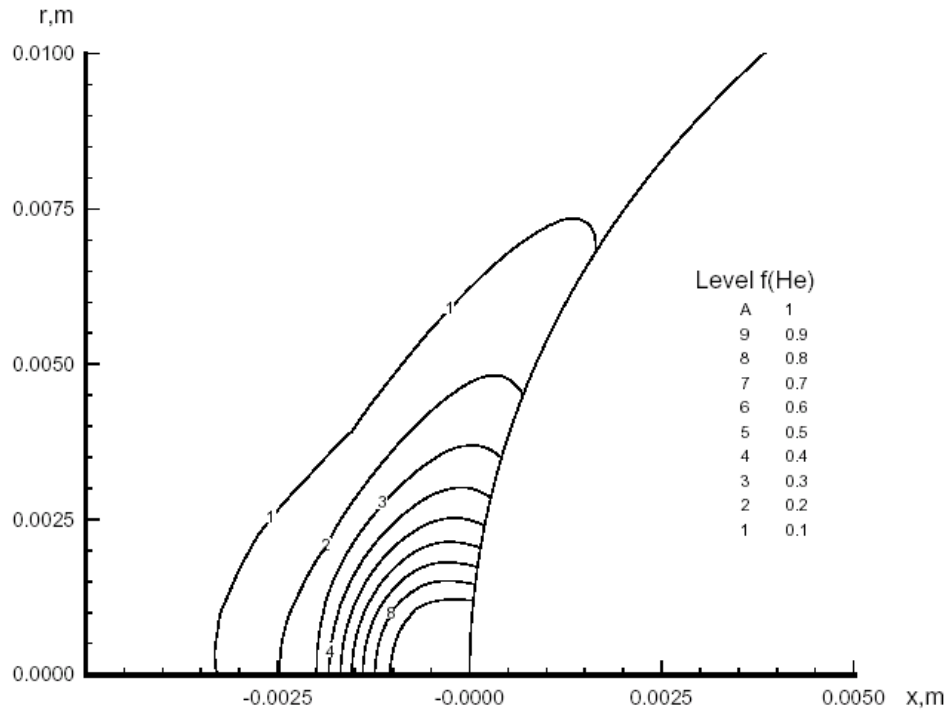


Fig. 6 Contours of helium mole fraction at $Re_{0,R} = 92.8$ and helium-to-air blowing factor $G_w = 0.7$.

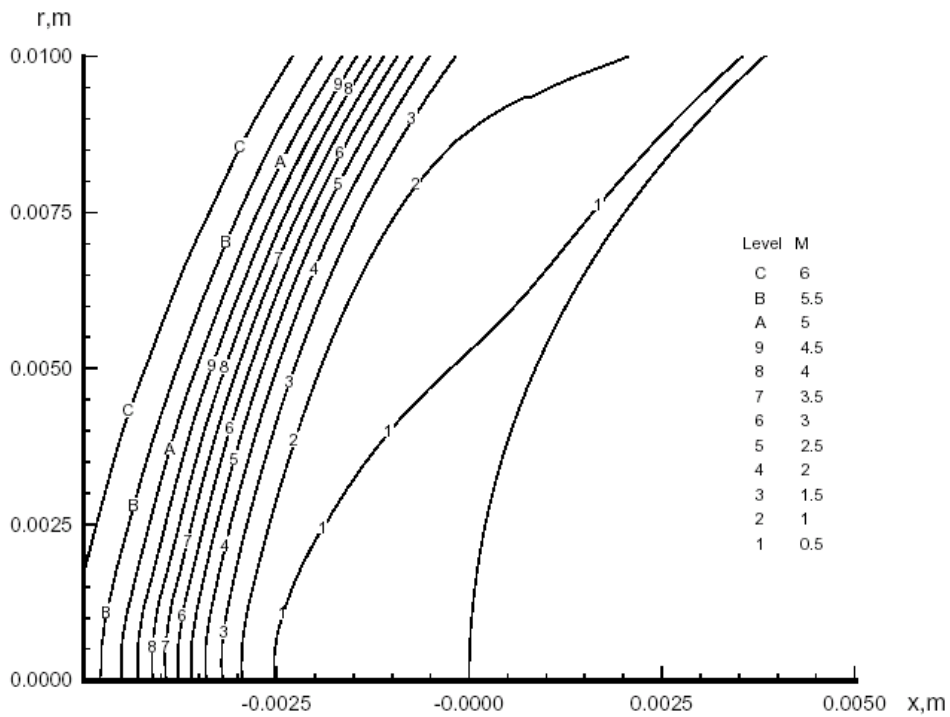


Fig. 7 Mach number contours at $Re_{0,R} = 92.8$ and helium-to-air blowing factor $G_w = 0.7$.

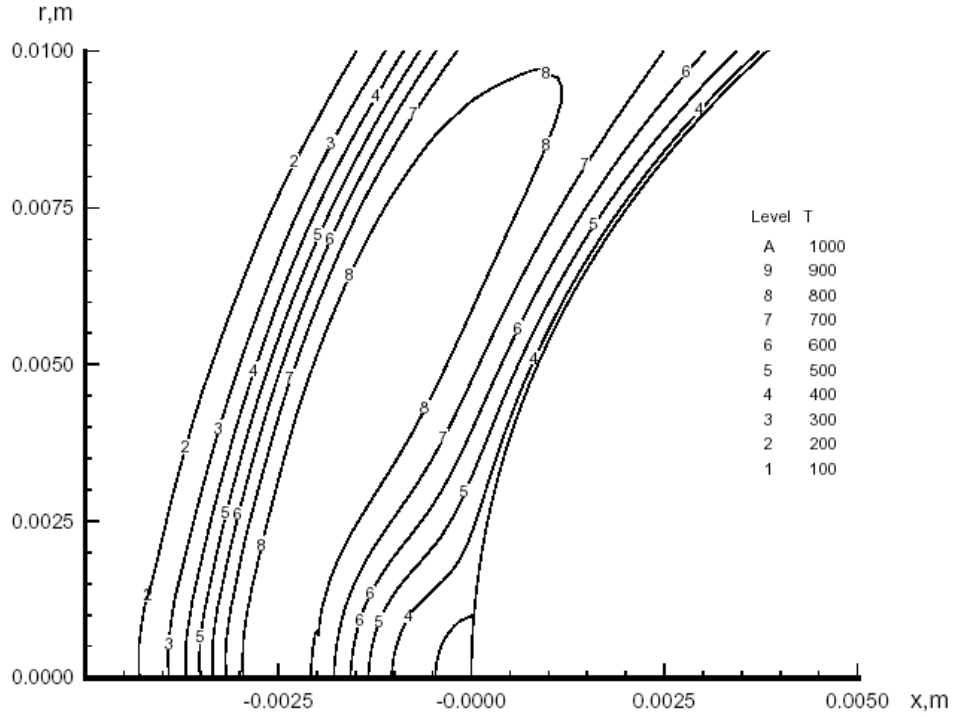


Fig. 8 Temperature contours at $Re_{\theta,R} = 92.8$ and helium-to-air blowing factor $G_w = 0.7$.

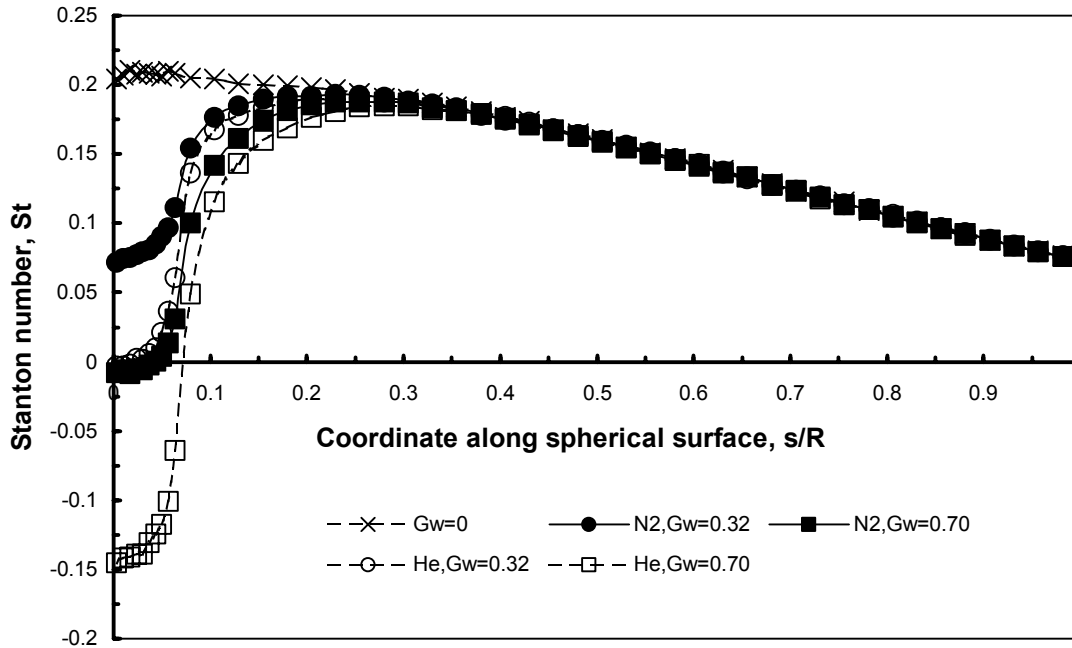


Fig. 9 Stanton number along the spherical surface at $Re_{\theta,R} = 92.8$ and various helium-to-air blowing factors.