Heat Transfer on a Hypersonic Sphere with Gas Injection

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Abstract. The interaction of a diffusing outgas flow from a sphere nose opposing a hypersonic free stream is studied numerically using 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 and 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.

Keywords: slot and uniform gas injection, hypersonic flow, heat protection, DSMC method
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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 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 [1-8].

The boundary-layer flow with gas blowing was studied in [6, 8-10]. Only few studies [11, 12] were conducted in the cases of transitional Knudsen numbers. Moss [12] found that mass injection significantly 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 heat transfer is zero.

The effect of injecting gaseous coolants on heat transfer in hypersonic perfect gas flow near blunt bodies was studied in Refs. 13-14 on the basis of the complete system of Navier-Stokes equations, and in Refs. 12, 15-18 on the basis of the thin viscous shock layer model [5]. Provotorov and Stepanov [17] 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 in Refs. 19-20.

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 [18] received by the method of two-layer thermal-indicator coating [21] confirms this conclusion. Other applications of the gas blowing include the reaction control systems [22] and a counterflow drag-reduction technique in high-speed systems [23].

In the present study, the interaction of a gas flow (air and helium), blowing diffusively from a nose of the sphere opposing a hypersonic freestream, is studied numerically by the direct simulation Monte-Carlo (DSMC) technique [7, 24-27] 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.

DSMC METHOD

The DSMC method [24] has been used in this study as a numerical simulation technique for low-density hypersonic gas flows. The DSMC/DS2G code [25] (ver. 3.2) is used for numerical calculations. Molecular collisions in air and helium are modeled using the variable-hard-sphere (VHS) molecular model [24]. The gas-surface interactions are assumed to be fully diffusive with full moment and energy accommodation. The code validation was tested by the author [26, 27] in comparing numerical results with experimental data [18, 21, 26, 27] related to the simple-shape bodies. As an example, the comparison of the DSMC recent numerical results with experimental data [21] 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 [21] (error bars in Fig. 1) was estimated as 8-12% at different flow regimes (see Refs. 18 and 21 for details). The numerical results correlate well with experimental data at $0.016 < Kn_{\infty,R} < 0.15$.

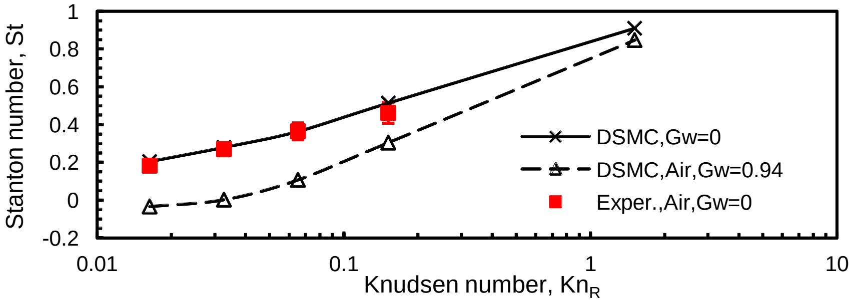


FIGURE 1. Stanton number vs Knudsen number at $M_\infty = 6.5$ and $t_w = 0.31$. Experimental data are from Ref. 21.

The methodology from Refs. 24 and 25 has been applied in computations. The cases that had been considered by Bird [25] 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 theses 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. 24 and 25, 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 [24]. The variation in cell width has been based on the geometric progression principle [24] 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 $1.5R$.

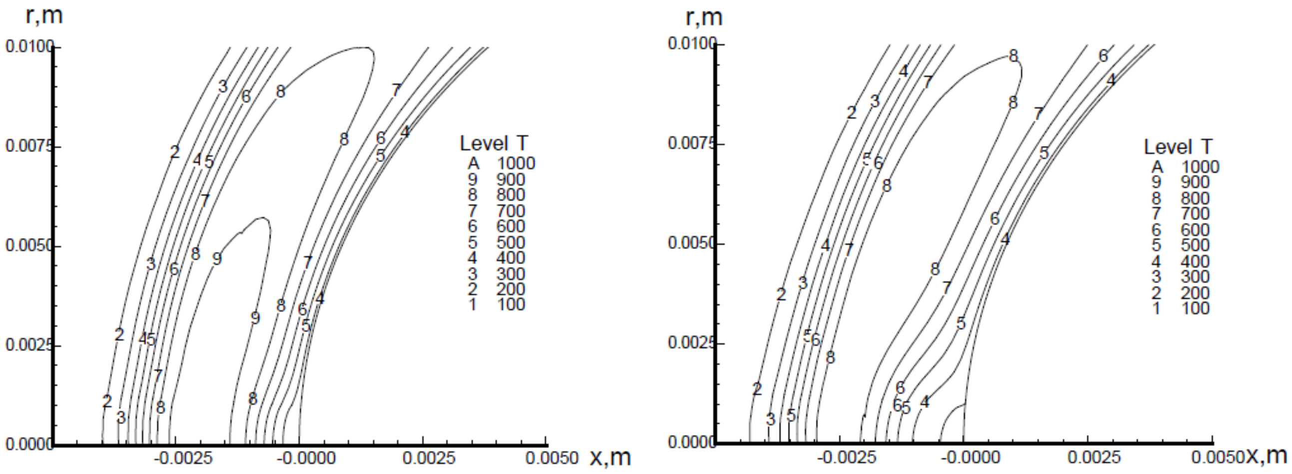
The DS2G program employed time averaging for steady flows [25]. About 95,000 samples have been studied in the considered cases. In all cases the usual criterion [24] for the time step Δt_m has been realized, $2\times10^{-8} \le \Delta t_m \le 1\times10^{-6}$ s. Under these conditions, aerothermodynamic 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 [25] 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 [18] 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.



a) Air-to-air injection

b) Helium-to-air injection

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

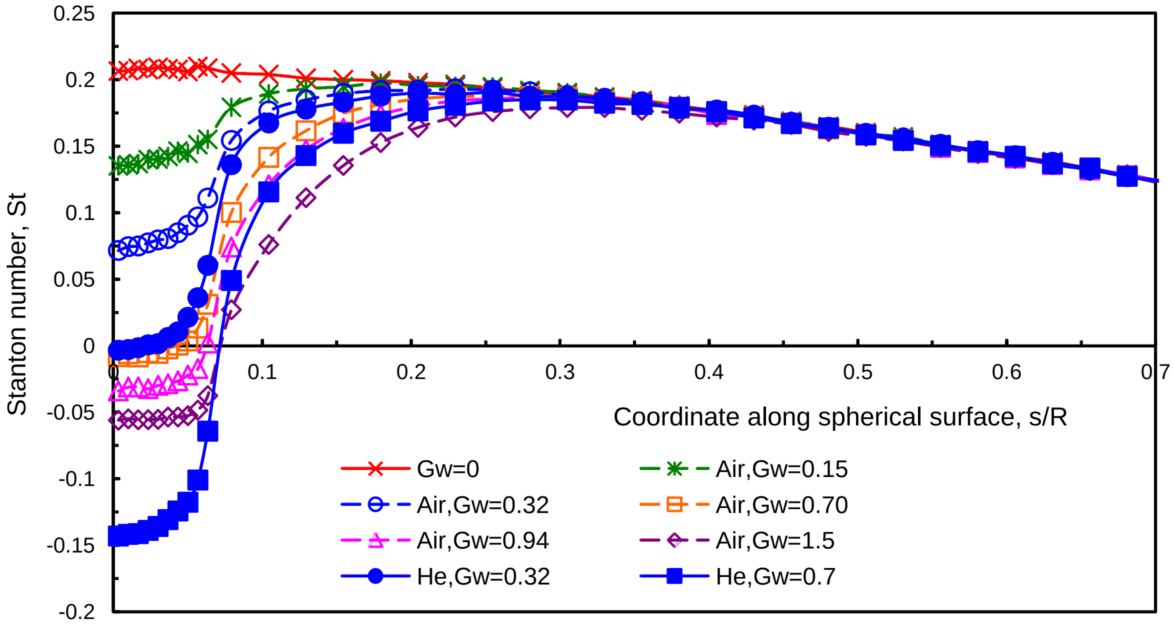


FIGURE 3. Stanton number along the spherical surface at $Kn_{\infty,R} = 0.0163$ and various air-to-air and helium-to-air mass blowing factors.

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 free-stream 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 $St_{\max}$ (see 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 [7, 24-27] as well as in aerothermodynamics [2, 3, 7, 26, 27]. 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 [21] 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 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 (see Fig. 4).

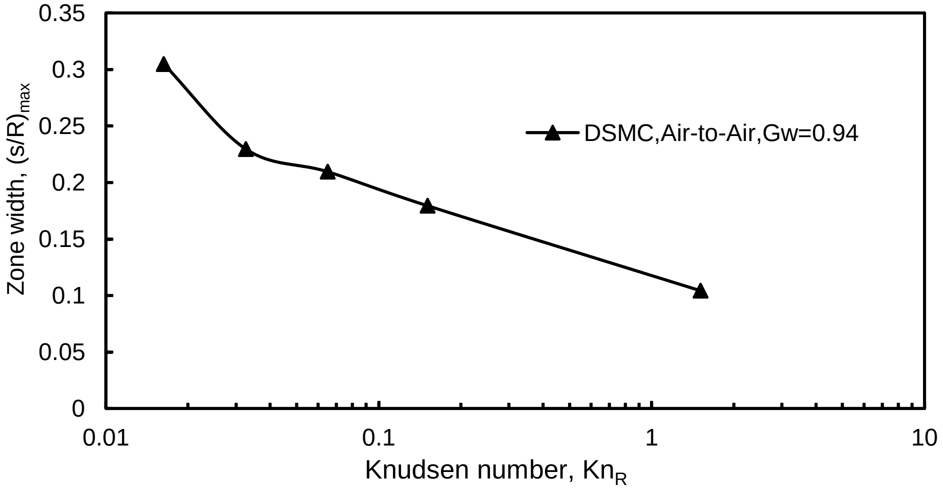


FIGURE 4. Width of the injection-influenced zone $(s/R)_{max}$ vs Knudsen number at $G_w = 0.94$.

At lower blowing factors, numerical results correlate well with experimental data of Botin [18], which were received by the method of two-layer thermal-indicator coating [21] 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. 5 and 6, respectively). Under these conditions, the injection influences heat-flux distributions primarily near the orifice.

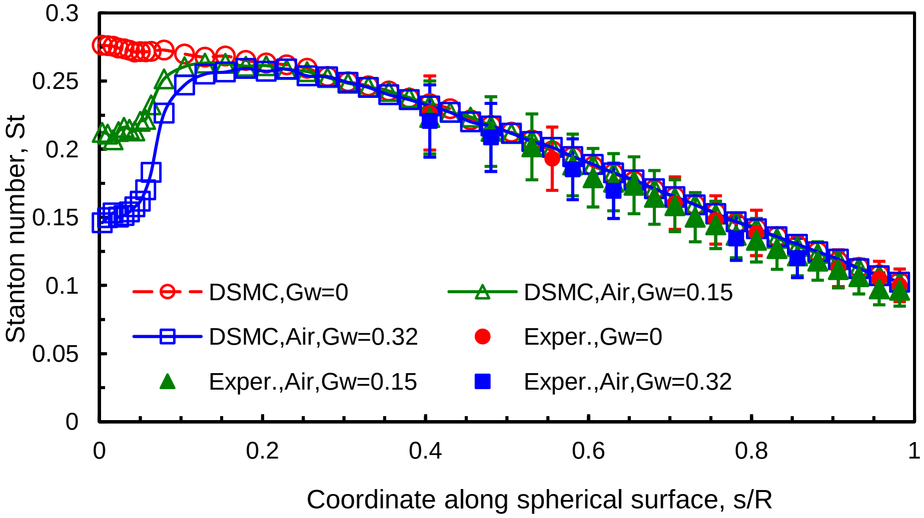


FIGURE 5. Stanton number along the spherical surface at $Kn_{\infty,R} = 0.0326$ and lower air-to-air mass blowing factors. Experimental data are from Ref. 18.

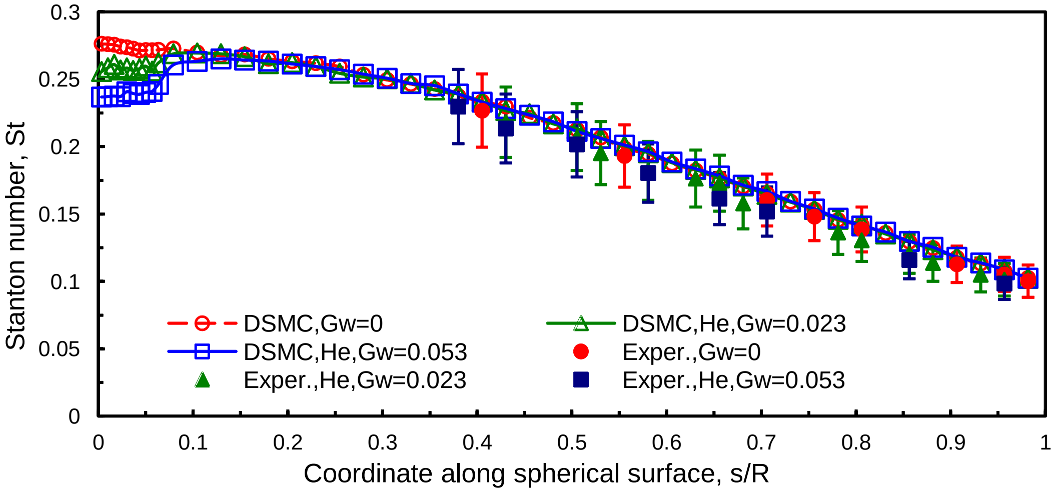


FIGURE 6. Stanton number along the spherical surface at $Kn_{\infty,R}$ = 0.0326 and lower helium-to-air mass blowing factors. Experimental data are from Ref. 18.

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.

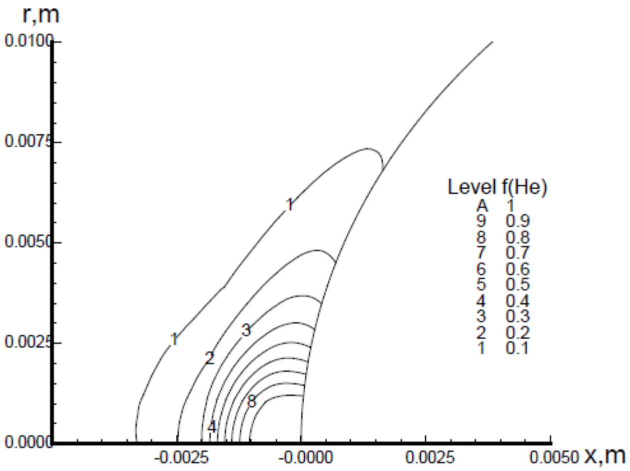


FIGURE 7. Contours of helium mole fraction f(He) at $Kn_{\infty,R}$ = 0.0163 and helium-to-air blowing factor G_w = 0.7.

The temperature contours and contours of helium mole fraction f(He) are shown in Figs. 2b and 7, respectively, for the case of the strong helium mass blowing factor (G_w = 0.7). The mole concentration of helium (Fig. 7) 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 [18].

CONCLUDING REMARKS

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 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 lower values of the Knudsen number, $Kn_{\infty,R} < 0.075$. The width of the injection-influenced displacement zone (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 blowing rates ($0.7 > G_w > 0.32$), diffuse outgas flow displaces completely the viscous layer off the sphere surface.

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