Numerical studies of hypersonic binary gas-mixture flows near a sphere

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1 Diffusive Effects in Binary Gas-Mixture Flows near a Sphere

Diffusion processes have a significant effect on the structure of a low-density gas mixture flow near blunt bodies [1], [2]. The effect of abnormal increasing of the temperature recovery factor at the stagnation point of a blunt body in the rarefied gas mixture flow was studied experimentally by Maise and Fenn [3]. The structure of rarefied gas mixture flows about a sphere was analyzed by Molodtsov and Riabov [4], [5] using numerical solutions of the Navier-Stokes equations. The normal shock wave structure in binary gas mixture was studied by Center [6] and Harnet and Muntz [7]. Direct Simulation Monte-Carlo (DSMC) technique was used by Bird [8], [9] and Plotnikov and Rebrov [10] to study the flow.

In the present study, diffusive effects in hypersonic flows of binary gas-mixtures near a sphere are studied using the DSMC method [9], [11] and numerical solutions of the Navier-Stokes equations [4]. The range of applicability of these techniques is estimated using the comparison of the results with experimental data [2] for N_2-H_2 and air-He mixtures. It is found that the diffusion and rarefaction affect the shock-wave width, allocation and width of high-pressure areas far from the surface, adiabatic temperature, pressure at the stagnation point, heat transfer, and the effectiveness of species separation and injected-gas penetration in the flow.

These features are illustrated by numerical results for N_2-H_2 mixture flow ($f_{N2,\infty}$ = 0.1) near a sphere for different regimes at Reynolds numbers $6 \leq Re_{0,R} \leq 100$ or Knudsen numbers $0.257 \geq Kn_{\infty,R} \geq 0.015$. Compared to a mono-component gas, the shock layer thickness increases, the mixture enrichment with heavy particles occurs in high pressure regions, and the adiabatic wall temperature rises. The Mach number contours in the flow at M_∞ = 6.6 past a sphere are shown in Fig. 1. At $Kn_{\infty,R} \geq 0.1$, the regime of the fully merged layer [12] is characterized by relatively smooth changing of the flow parameters in the flow-field (see Fig. 1 (*left*)). Under

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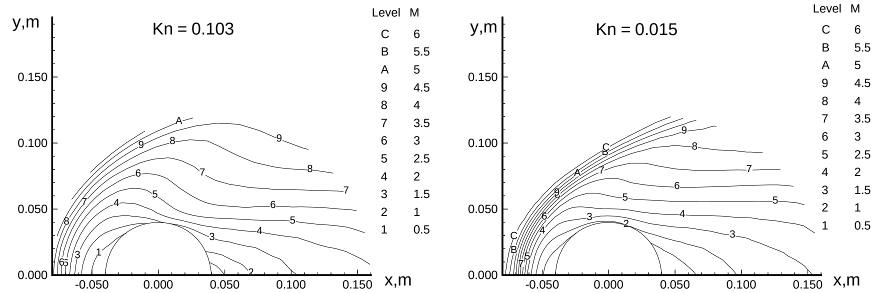

Fig. 1 Mach number contours in the flow of N_2-H_2 mixture past a sphere at $M_\infty = 6.6$: (*left*) $Kn_{\infty,R} = 0.103$ and (*right*) $Kn_{\infty,R} = 0.015$

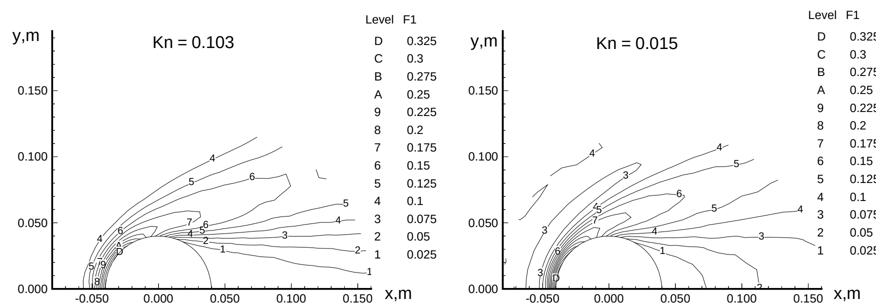

Fig. 2 Nitrogen concentration contours in the flow of N_2-H_2 mixture past a sphere at $M_\infty = 6.6$: (*left*) $Kn_{\infty,R} = 0.103$ and (*right*) $Kn_{\infty,R} = 0.015$

the viscous-layer-regime conditions [12] at $Kn_{\infty,R} \leq 0.03$, the strong shock wave near the sphere causes significant gradients of flow parameters (see Fig. 1 (*right*)), and profiles of nitrogen concentration become sensitive to the pressure gradients here. The later is illustrated in Fig. 2 for considered flow regimes.

Diffusive effects become significant in the shock wave, where the enrichment of the mixture with light component occurs (see Figs. 2 and 3), near the sphere front, and in the area of high pressure. The latter points to the domineering role of the baro-diffusion while components separate. The nitrogen profiles f_{N2} are sensitive to the pressure gradients at the stagnation stream-line near a sphere, which are different for the fully merged layer and viscous layer regimes shown in Fig. 3.

The profiles of the stream velocity U and diffusion velocities in the flow of nitrogen-hydrogen mixture at the stagnation stream-line near a sphere are shown in Fig. 4 for different flow regimes. As the rarefaction of gas media decreases, the structure of the diffusive zones changes significantly. At low values of the Knudsen

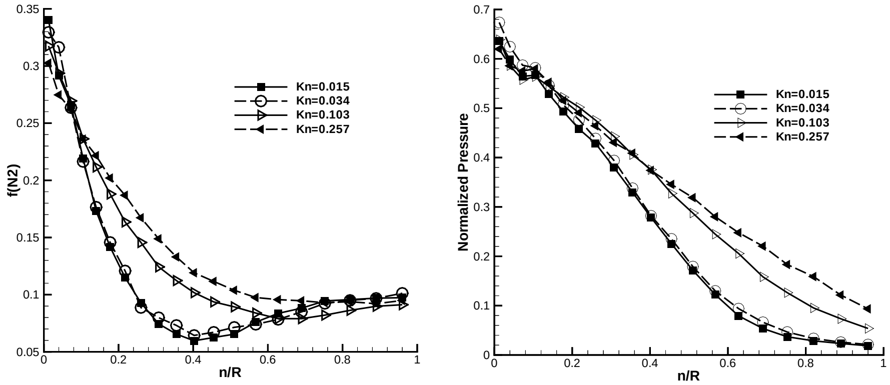

Fig. 3 The profiles of nitrogen mole concentration f_{N2} (*left*) and normalized pressure $p/\rho_\infty U_\infty{}^2$ (*right*) in the flow of N_2-H_2 mixture near the stagnation line of a sphere at $M_\infty = 6.6$

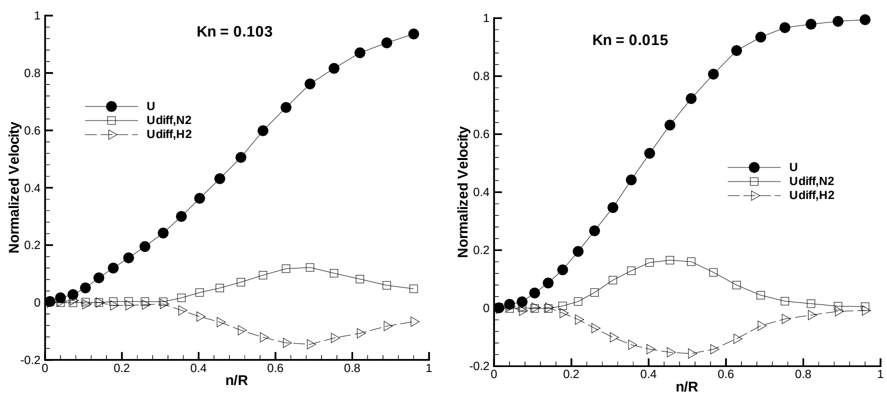

Fig. 4 The profiles of the steam and species diffusion velocities in the flow of N_2-H_2 mixture near the stagnation line of a sphere at $M_\infty = 6.6$: (*left*) $Kn_{\infty,R} = 0.103$ and (*right*) $Kn_{\infty,R} = 0.015$

number, the maximum magnitude of the diffusion velocity of heavy component (N_2) correlates with the minimum magnitude of the diffusion velocity of light component (H_2), and it corresponds to the maximum concentration of light species in the shock wave near a sphere (see, also, Fig. 3 (*left*)).

The dissipative viscous and diffusion processes have the major influence on the temperature distribution: the overall temperature and translational temperature can be higher than the stagnation temperature in the flow. At the stagnation point the gas temperature slightly increases near the thermo-isolated wall [3], [4]. For fully-merged-layer diatomic-gas flow regime, the rotational-translational relaxation occurs in the whole area of the flow. In viscous-layer regime, nonequilibrium effects are observed in the shock-wave and in the area behind it.

2 Comparison between Numerical Solutions and Experimental Data

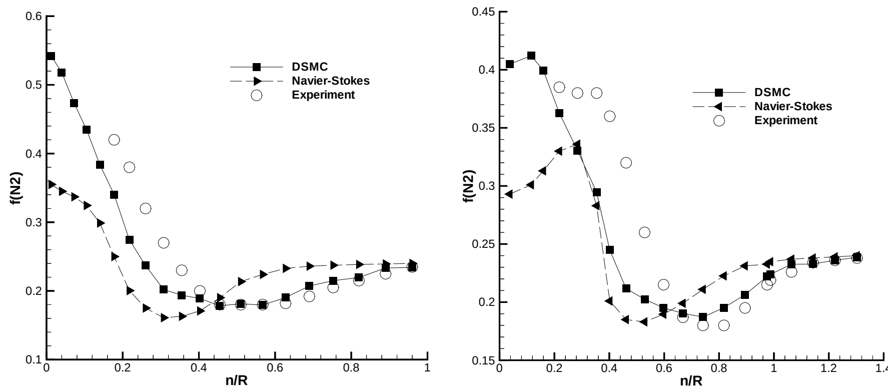

Fig. 5 The profiles of nitrogen mole concentration in the flow of N_2-H_2 mixture at $M_\infty = 3.5$ and $Kn_{\infty,R} = 0.025$ near the stagnation line of a sphere (*left*) and along the normal at $s = 1.02R$ (*right*)

Only few experiments have analyzed the structure of rarefied binary-mixture flows near a sphere [1], [2]. In Fig. 5 the DSMC results are compared with the experimental data of Rebrov [2] concerning the nitrogen concentration profiles in the flow of nitrogen-hydrogen mixture at $Kn_{\infty,R} = 0.025$, $f_{N2,\infty} = 0.24$ and $M_\infty = 3.5$. The numerical results are in a good agreement with the experimental data at the stagnation stream line $s = 0$ (*left*), as well as along the normal far from the line at $s = 1.02R$ (*right*). The concentration f_{N2} of the heavier component near the sphere's critical point (see Fig. 5 (*left*)) increases approximately two times its concentration in the upstream flow. The reason for this increase is the baro-diffusion effect induced by high pressure gradients. The same effect occurs in the zone of high pressure at some distance ($s = 1.02R$) from the body far from the stagnation line. This zone (see Fig. 2 and Fig. 5 (*right*)) is like a toroidal cloud of N_2 near the sphere. In both cases the DSMC results correlate with the experimental data [2] much better than the continuum-approach solutions.

The difference between the DSMC results and Navier-Stokes solutions was also found in the analysis of temperature and pressure profiles at the stagnation stream line (see Fig. 6). The shock wave became broader compared to the streamlining of the spherical surface by the mono-component gas (H_2), and the gas temperature slightly increased near the wall (see Fig. 6 (*left*)). The pressure parameters are significantly different because of the relaxation processes mentioned above. The Navier-Stokes equations were solved under the conditions of the one-temperature approximation and rotational-translational equilibrium.

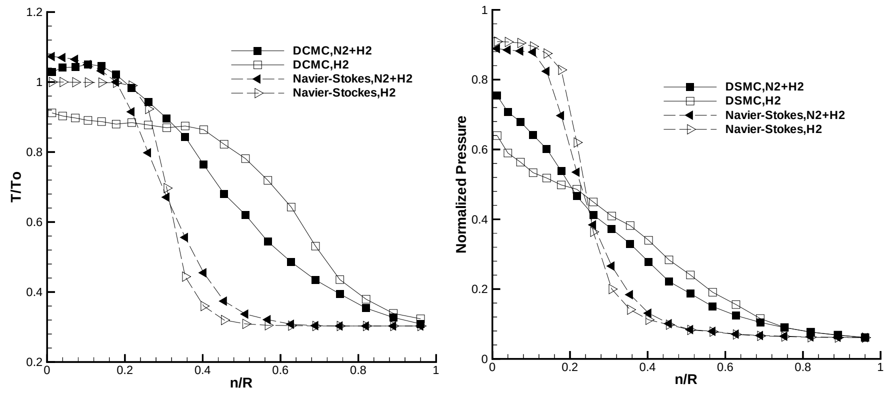

Fig. 6 The profiles of overall temperature T (*left*) and normalized pressure $p/\rho_\infty U_\infty{}^2$ (*right*) in the flow of N_2-H_2 mixture near the stagnation line of a sphere at $M_\infty = 3.5$ and $Kn_{\infty,R} = 0.025$

3 Heat Transfer on a Sphere with Diffuse Gas Injection

Numerical and experimental studies [13], [14] of aerothermodynamics of hypersonic vehicles showed 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 moderate Knudsen numbers $Kn_{\infty,R}$. Mass injection can be considered as an effective way of the reduction of heat transfer to the surface in this area [14], [15], [16].

In the present study, the interaction of a gas flow (air and helium), blowing diffusively from a nose of the sphere opposing a hypersonic free stream, is studied numerically by the DSMC technique [9], [15] under the transition rarefied-gas-flow conditions at Knudsen numbers $Kn_{\infty,R}$ from 0.016 to 1.5 and blowing factors G_w (the ratio of out-gas mass flux to upstream mass flux) from 0.023 to 1.5.

Helium has been selected as out-gas to study the role of diffusive effects of blowing. Under the transition flow conditions ($Kn_{\infty,R} = 0.0163$), the size of the displacement zone, $(s/R)_{max}$ is larger than that one in the case of air-to-air blowing [15] due to significant differences in diffusive properties of helium and air. At the strong helium mass-blowing factor ($G_w = 0.7$), the mole concentration of helium is still significant (up to the value of 0.1) at the distance of $0.2R$ in the upstream flow direction and about $0.47R$ along the sphere surface (see Fig. 7 (*left*)).

The temperature contours are disturbed more pronouncedly than in the case of air-to-air blowing. The distributions of the Stanton number St along the spherical surface at various blowing factors are shown in Fig. 7 (*right*). For the considered transitional flow regime conditions, even at moderate mass-blowing factors ($0.7 \geq G_w \geq 0.32$), diffuse out-gas flow displaces completely the viscous layer off the sphere surface, and the heat transfer is zero. The similar effect was discussed in the experimental study by Botin [16].

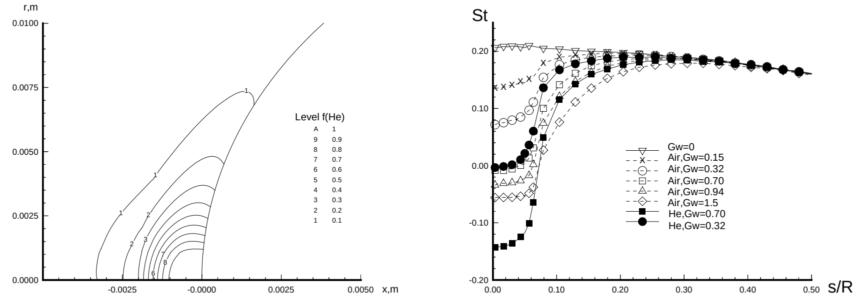

Fig. 7 *Left*: Contours of helium mole concentration near a sphere at $Kn_{\infty,R} = 0.0163$ and helium-to-air mass blowing factor $G_w = 0.7$ and *Right*: Stanton number along the spherical surface at $Kn_{\infty,R} = 0.0163$ and various air-to-air and helium-to-air mass blowing factors

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