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SHORTER COMMUNICATION

EFFECT OF WALL ACCOMMODATION ON HEAT TRANSFER AND PRESSURE IN THE STAGNATION REGION OF BLUNT BODIES†

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NOMENCLATURE

c_p^*,	isobaric specific heat;
Kn,	Knudsen number, $Kn = \Lambda^*/L^*$;
L^*,	nose radius;
M_∞,	freestream Mach number at frozen vibration, $M_\infty = V_\infty^*/(\gamma R^* T_{TR\infty}^*)^{1/2}$;
p,	pressure, $p = p^*/\rho_\infty^* V_\infty^{*2}$;
$\mathbf{q}$,	heat flux vector, $\mathbf{q} = \mathbf{q}^*/\rho_\infty^* V_\infty^{*3}$;
R^*,	specific gas constant;
Re_∞,	freestream Reynolds number, $Re_\infty = \rho_\infty^* V_\infty^* L^*/\mu_\infty^*$;
St,	stagnation point Stanton number, $St = \lvert\mathbf{q}_0\rvert/[c_{pTR}^*(T_{TR\infty}^* - T_w^*)/V_\infty^{*2} + \frac{1}{2}]$;
T^*,	temperature;
V_∞^*,	absolute value of the freestream velocity.

Greek symbols

α,	thermal accommodation coefficient;
γ,	ratio of specific heats at frozen vibration;
Λ^*,	mean free path of the gas molecules;
μ^*,	viscosity coefficient;
ρ^*,	density;
σ,	accommodation coefficient for tangential momentum.

Subscripts

TR,	translation and rotation;
V,	vibration;
w,	wall quantities;
0,	stagnation point quantities;
∞,	freestream quantities.

Superscript

$*$,	dimensional quantities.

1. INTRODUCTION

Various aspects of the flow field prevailing around blunt-nosed re-entry vehicles moving with hypersonic speed in the upper atmosphere have been studied by many authors. In the present investigation, the stagnation region of an axisymmetric body is considered in the merged layer regime. Here, viscous effects play a role in the entire region from the free stream to the body surface. Further, velocity slip and temperature jump at the surface strongly influence the flow field even in front of a highly cooled body, as has been shown by Jain and Adimurthy [1]. Their results have demonstrated, that the gas may be treated as a continuum up to relatively high freestream Knudsen numbers. This study dealing with the flow of a pure ideal gas has been extended to the flow of a multicomponent nonequilibrium mixture of reacting gases by Scott [2] and Hendricks [3]. The influence of vibrational relaxation of a pure diatomic gas has been investigated recently [4]. In these papers the slip effects have been taken into account, but only the case of full accommodation of momentum and translational energy has been considered. In the present study, the effect of a lower degree of accommodation is examined.

2. BOUNDARY VALUE PROBLEM AND METHOD OF SOLUTION

The balance equations governing the stationary flow and the assumptions concerning the behaviour of the gas are the same as those used earlier [4]. That is, a pure diatomic gas is considered. Since the dissociation of the gas molecules is neglected, conclusions may be drawn only for cases, in which the freestream density is less than a certain critical value depending on the freestream velocity and the nose radius of the body. In such cases, only a small effect of the variation of vibrational energy on the heat transfer to a highly cooled body has been found [4]. This effect could become more important at a lower degree of accommodation of momentum and translational energy. Therefore, here the vibrational energy is taken into account too.

Further, as in the earlier paper [4], the gas is assumed to be thermally perfect and calorically perfect at frozen vibration. Sutherland's formula is used for the coefficient of viscosity, and the Prandtl numbers at frozen vibration and at vibrational equilibrium are taken to be equal to the same constant.

On the body surface, first order velocity slip and temperature jump conditions are fulfilled.

Since the flow is studied in the vicinity of the stagnation streamline, the flow variables are expanded into series about this line. These series are truncated following the concept of local similarity, which may be used for hypersonic flow. The resulting boundary-value problem has been solved numerically with the method of successive accelerated replacement, which has been used previously by Dellinger [5], Jain and Adimurthy [1], Kumar and Jain [6], Hendricks [3] and in the paper cited above [4].

3. RESULTS AND DISCUSSION

Numerical solutions have been obtained for the flow of nitrogen. The results are discussed for two examples with the freestream conditions and surface temperature given in Table 1.

Table 1. Freestream conditions and surface temperature for the examples

Number of example	1	2
L^* [cm]	30	30
V_∞^* [km/s]	4.7	6
ρ_∞^* [10^{-8} g/cm^3]	2	0, 32
$T_{TR\infty}^*$ [K]	180	180
T_w^* [K]	1000	1000
M_∞	17.2	21.9
Re_∞	2364	483
Kn_∞	0.011	0.068

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In Fig. 1 the contribution of the vibrational energy to the stagnation point heat transfer is compared with that of the translational and rotational energy. It can be seen, that the Stanton numbers St_V and St_{TR} depend only weakly on σ, that is on the accommodation of tangential momentum. A stronger dependence on α_{TR}, that is on the accommodation of translational and rotational energy, is found. Especially, the decrease of St_{TR} with decreasing α_{TR} is accompanied by an increase of St_V. That is, a smaller flux of translational and rotational energy from the hot gas to the cold wall leads to a higher flux of vibrational energy in this direction. Thus the relative importance of the latter increases with decreasing α_{TR}. Nevertheless, the absolute value of the maximum contribution of the vibrational energy, which is reached practically at $\alpha_{TR} = 10^{-3}$, is very small. This is true even in the case of full accommodation of the vibrational energy considered here. Further calculations, which are not given in the figure, showed, that St_V decreases with α_V, that is with the accommodation of vibrational energy, while St_{TR} remains practically unchanged. The investigation of example 2 revealed an analogous behaviour of St_V.

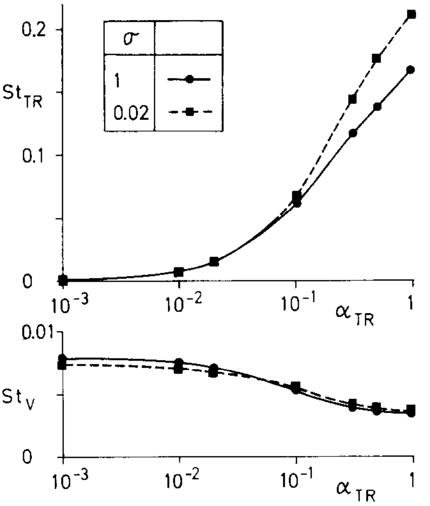
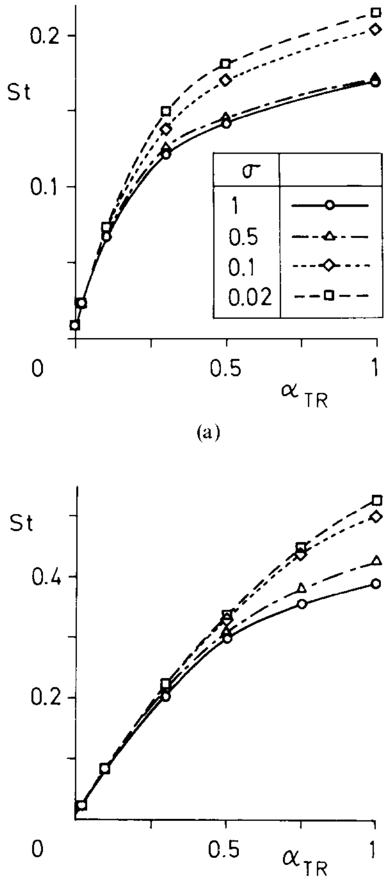


FIG. 1. Contributions St_{TR} of translational and rotational energy and St_V of vibrational energy to the stagnation point heat transfer St for example 1 at $\alpha_V = 1$.

Figure 2 shows the total stagnation point heat transfer. Its relative decrease with decreasing α_{TR} is found to be even more important in the second example. That is, a reduction of α_{TR} from the value 1 to the value 0.1 leads to a heat-transfer reduction of at least 60% for example 1 and of at least 80% for example 2. At $\alpha_{TR} = 0.02$ the heat transfer is already reduced by at least 87% and 94.3%, respectively. This tendency becomes even more pronounced with decreasing α_V giving rise to a relatively small decrease of the higher values of St at $\alpha_{TR} = 1$ and to a relatively great decrease of the smaller values of St at smaller α_{TR}.



(a)

(b)

FIG. 2. Total stagnation point heat transfer at $\alpha_V = 1$: (a) for example 1, (b) for example 2.

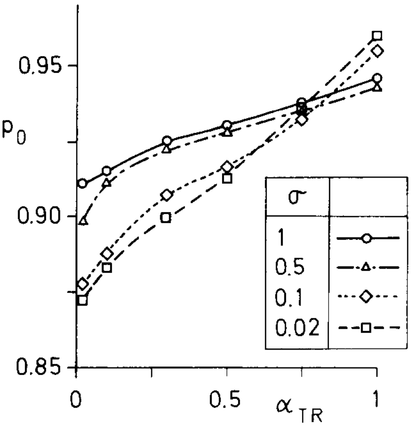


FIG. 3. Stagnation point pressure for example 2.

At the discussion of the effect of the accommodation coefficients on the stagnation point pressure, a special property of the results of the present calculation must be taken into consideration. That is, the pressure distribution along the stagnation streamline shows some oscillations near the wall. This is a numerical effect, which may be removed by decreasing the acceleration factor controlling the convergence of the iteration and by increasing the number of mesh points. But this would lead to a considerably longer run time on the computer. Thus an averaged curve has been used to determine the pressure at the stagnation point. As for the first example, the change caused by the variation of the accommodation coefficients is in the order of magnitude of the error. The results for the second example are presented in Fig. 3. Also in this case, no influence of the value of α_V has been found. The error introduced by the averaging procedure, which of course is not the only error, has the order of 0.1. Therefore, it may be deduced that the pressure is decreased by 2% to 11%, depending on σ, when α_{TR} is decreased from the value 1 to the value 0.02. In conclusion, from these examples it appears, that the pressure is not affected very much by the variation of the accommodation coefficients.

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