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CALCULATIONS OF INVISCID HIGH SPEED DISSOCIATING GAS FLOW OVER A CONE AT INCIDENCE

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ABSTRACT

The chemically reacting inviscid flow of pure nitrogen over a blunt cone (half angle 13.5°) at an incidence of 30° has been investigated using a finite volume computational technique. The freestream conditions correspond to those which are typical of the test section of high enthalpy experimental facilities. The characteristic cone size was varied to produce flows which span the non-equilibrium regime. It has been found that the pitching moment on the body is a strong function of bluntness and that there are small but significant chemical effects superimposed on the bluntness effects. The effect of chemistry is most complicated for the bluntest body.

INTRODUCTION

In chemically reacting flow, the ratio of a characteristic body dimension to a characteristic chemical length L_{chem} behind the normal portion of the bow shock can be used as a 'reaction rate parameter'. For the typical flight trajectories of hypersonic aerospace planes conditions range from chemically frozen flow, through a regime of non-equilibrium, to equilibrium flow where chemical equilibrium can be achieved within each fluid particle while it traverses the vehicle.

Stalker[1989] developed an analytical model to show that the transition of pitching moment from the limit of frozen to equilibrium chemistry is not monotonic and this was supported by earlier numerical results for a blunted flat plate [Macrossan, 1990] and for a sharp cone [Macrossan and Pullin, 1994]. Here we calculate the chemically reacting inviscid flow of nitrogen over a blunt cone (half angle 13.5°) at an incidence of 30° using a finite volume computational technique [Pullin, 1980; Macrossan, 1989]. The dissociation reactions for N_2, and the similar reactions for O_2, are important in high speed air flow. The freestream conditions ($u_\infty = 6.696$ km/s, $\rho_\infty = 9.974 \times 10^{-3}$ kg/m^3, $T_\infty = 4469$ K, $\alpha_\infty = 0.0113$, $M_\infty = 5$, $L_{chem} = 0.0032$ m) are typical of a free piston shock tunnel. The stagnation enthalpy ($\approx 28MJ/kg$) is 83% of the dissociation energy.

There were 24×50 cells in the cross-flow plane roughly normal to the blunt nose surface; this changed to 48×100 crosss-flow cells downstream. There were 27 cross-flow planes along the nose in the streamwise direction and 53 more to a distance $x \approx 14R_n$. Calculations with different grids for chemically frozen flow indicated that the average error in flow properties was $\approx 1\%$ and that the error in the pitching moment was $< 0.5\%$.

The windward and leeward forces are considered seperately since it is possible that in short duration test flows in high enthalpy shock tunnels the windward flow will reach steady state while the leeward flow may not. Earlier work for a sharp cone [Macrossan and Pullin, 1994] showed that the chemical effects on the windward and leeward flow are quite different.

WINDWARD FORCES

Figure 1 shows the data for $C_{z,w}$, the contribution to the pitching moment coefficient made by the forces acting on the windward surface only. For all values of the reaction rate parameter R_n/L_{chem}, where R_n is the blunt nose radius,

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$C_{z,w}$ has a sharp minimum at $x/R_n \approx 1.3$, where x is the cone length; this is a very blunt cone consisting almost entirely of the spherical nose. For larger values of x/R_n (sharper cones) the pitching moment increases towards a limiting value.

The effect of different values of R_n/L_{chem}, is at most 2% which, though small, can be significant [Stalker, 1989]. This chemical effect can be seen more clearly in figure 2 which shows data for the windward pitching moment *vs.* R_n/L_{chem}, for three values of x/R_n. In each case the regime of chemical non-equilibrium is given approximately by $3 \times 10^{-3} \leq R_n/L_{chem} \leq 10^3$.

The results for the least blunt cone, $x/R_n = 12.2$, are very close to those found previously for a sharp cone [Macrossan and Pullin, 1994]. In those cases and also for a greater degree of bluntness, $x/R_n = 4.5$, the values of moment for frozen chemistry ($R_n/L_{chem} \to 0$) and equilibrium chemistry ($R_n/L_{chem} \to \infty$) are similar while in the intermediate (non-equilibrium) regime $C_{z,w}$ does not always lie between the limiting values. In all cases the pitching moment begins to decrease from its equilibrium value at $x/R_n \approx 1000$ and there is a local minimum in $C_{z,w}$ in the non-equilibrium regime. For the sharpest cone the rise in $C_{z,w}$ after the local minimum is monotonic towards the value for frozen chemistry; for the blunter cones, the initial rise is followed by a fall which is slight for the moderately blunted cone, $x/R_n = 4.5$, but much greater for $x/R_n = 2.2$.

LEEWARD FORCES

Figure 3 shows data for $C_{z,l}$, the leeward contribution to the pitching moment, *vs.* x/R_n for different values of R_n/L_{chem}. In contrast to the windward data (figure 1), the effect of chemistry on $C_{z,l}$ is of the order of 25%. The effect of bluntness is also about 25%, somewhat less than the bluntness effect on the windward pitching moment.

For the limiting cases of frozen and equilibrium chemistry, there is a local minimum in pitching moment coefficient for a bluntness of $x/R_n \approx 3$. This is similar to the behaviour of the windward pitching moment for all values of reaction rate parameter, but here the bluntness effects are negligible for $x/R_n > 10$. The local minimum in the curve is least severe for $R_n/L_{chem} = 9.3$, *i.e.* bluntness effects are moderated by non-equilbrium chemistry effects. Conversely, bluntness effects are most pronounced for the limiting cases of frozen and equilibrium chemistry.

Figure 4 shows data for $C_{z,l}$ *vs.* R_n/L_{chem} for different values of x/R_n. Unlike the case for the windward pitching moment (figure 2), the general trend is the same for all degrees of bluntness; the values for frozen and equilibrium chemistry differ by 1 - 4 % and there is large departure in the non-equilibrium regime of 40 - 50% for the low values of x/R_n (blunt cones) and about 20 - 30% for the high values of x/R_n (relatively sharp cones). The departure from the equilibrium chemistry limit occurs at $R_n/L_{chem} \approx 3 \times 10^4$, which is more than an order of magnitude higher than for the windward flow. The maximum deviation from the equilibrium value of $C_{z,l}$ occurs at $R_n/l_{chem} \approx 30$ for $x/R_n = 12.2$ and at $R_n/L_{chem} \approx 3$ for $x/R_n = 2.2$.

CONCLUSIONS

It has been found that the windward force pitching moment is a strong function of bluntness and that there are small but significant chemical effects superimposed on the bluntness effects. For the leeward forces, the effects of bluntness and chemical reaction rate on the pitching moment are similar in magnitude. The variation of pitching moment between the limiting cases is not always monotonic; it is a strong function of bluntness (figure 2). For very blunt cones, an assumed design value of $C_{z,w}$ between the limits set by equilibrium and frozen chemistry flow calculations would be reasonable; for moderately blunted and sharp cones it would not.

Bluntness effects on the leeward flow for equilibrium and frozen chemistry conditions are less than for the windward flow and are reduced even further for values of the reaction rate parameter $\approx O(1)$ (see figure 3). There are strong chemical effects on the leeward forces and these chemical effects extend over a greater range of reaction rate parameter R_n/L_{chem} than for the windward flow.

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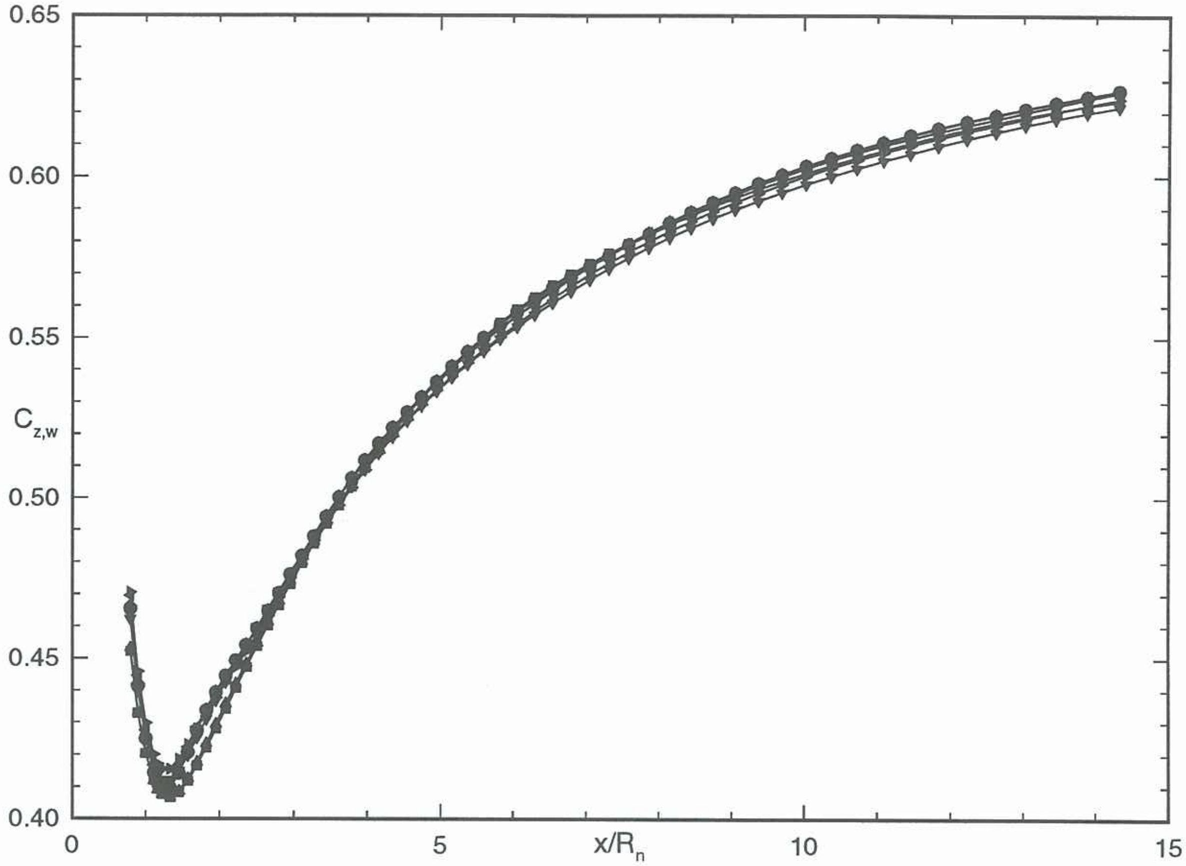

Fig 1: Windward pitching moment *vs.* bluntness. ■, frozen; ▲, $R_n/L_{chem} = 0.031$; ▼, $R_n/L_{chem} = 0.31$; ▶, $R_n/L_{chem} = 9.3$; ◀, $R_n/L_{chem} = 93$; ◆, $R_n/L_{chem} = 930$; ●, equilibrium.

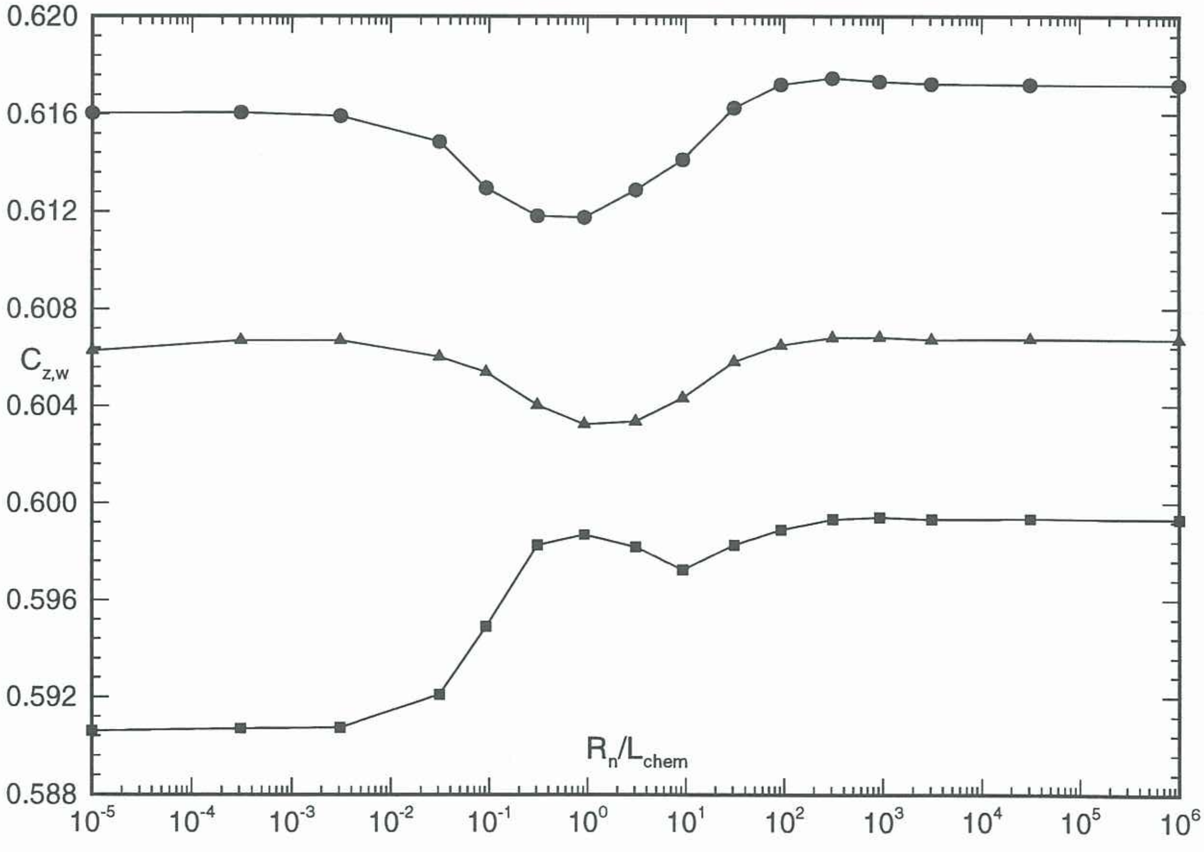

Fig 2: Windward pitching moment *vs.* reaction rate. ■, $x/R_n = 2.2$; ▲, $x/R_n = 4.5$; ●, $x/R_n = 12.2$.

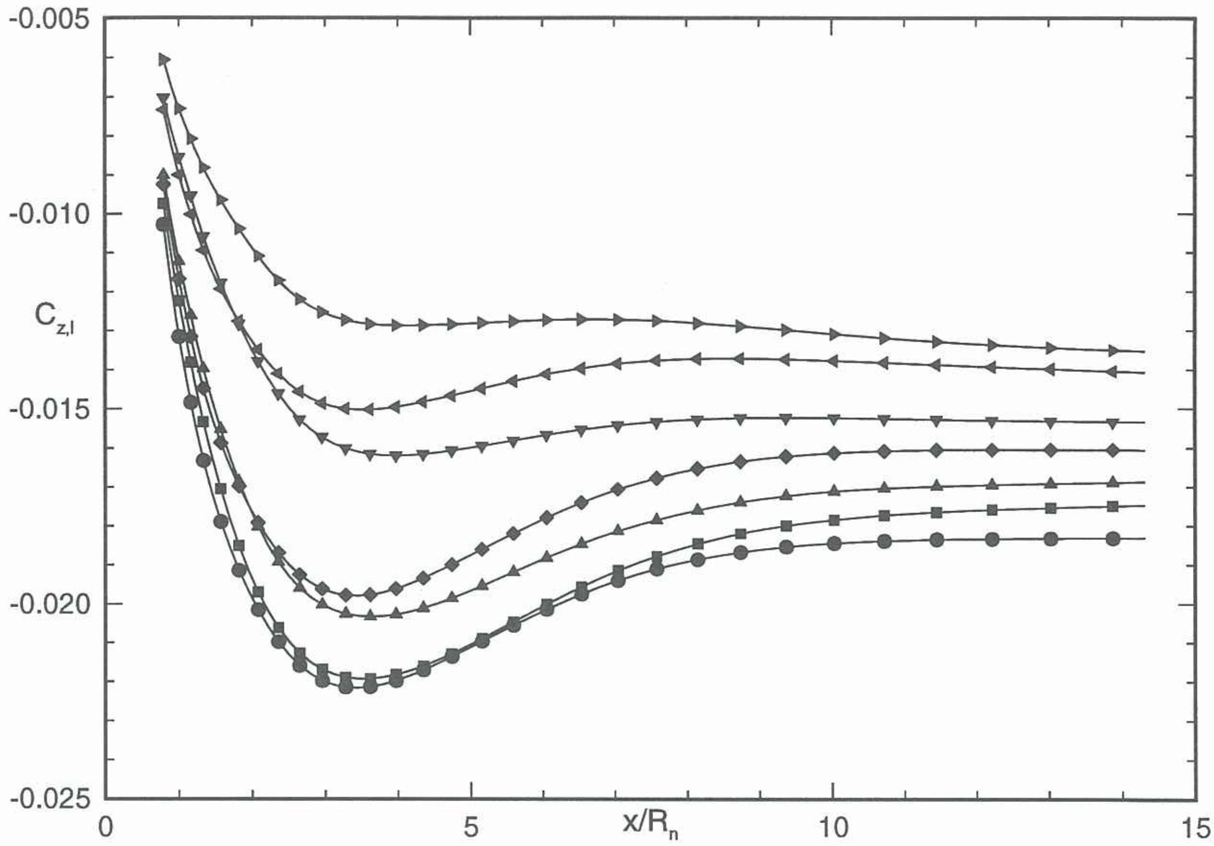

Fig 3: Leeward pitching moment *vs.* bluntness. ■, frozen; ▲, $R_n/L_{chem} = 0.031$; ▼, $R_n/L_{chem} = 0.31$; ▶, $R_n/L_{chem} = 9.3$; ◀, $R_n/L_{chem} = 93$; ◆, $R_n/L_{chem} = 930$; ●, equilibrium.

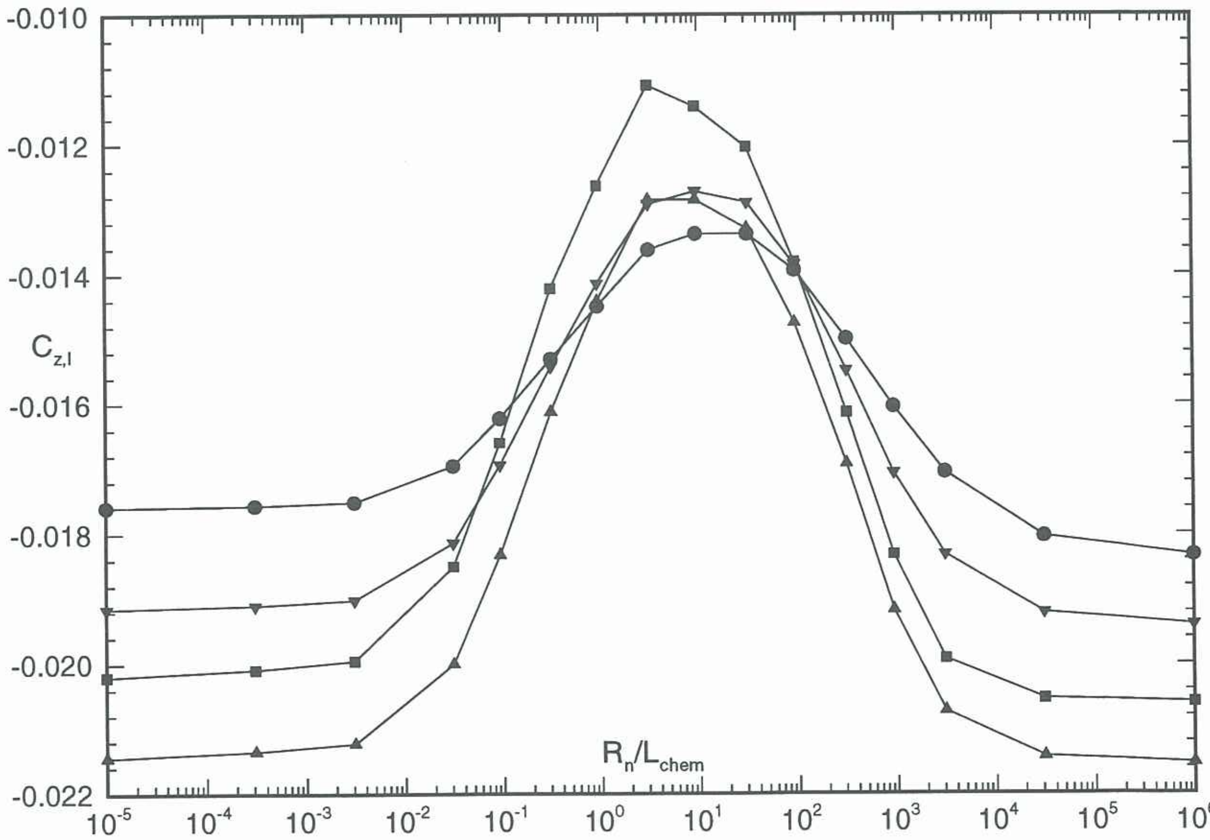

Fig 4: Leeward pitching moment *vs.* reaction rate. ■, $x/R_n = 2.2$; ▲, $x/R_n = 4.5$; ▼, $x/R_n = 7.0$; ●, $x/R_n = 12.2$.