to be associated with an asymmetry in the vortex flowfield on the lee side, the asymmetry in the wing rolling moments must be associated with a similar asymmetry in the wing vortex flowfield. The fact that the asymmetries occur as the slenderness is increased suggests that the cause of the vortex asymmetry is a hydrodynamic instability in the vortex flowfield resulting from the crowding together of the vortices as the apex angle is decreased. Furthermore, the fact that the separation point is fixed at the leading edge for delta wings implies that the asymmetry in separation point on a body of revolution is not necessarily an essential feature of vortex asymmetry.

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A Model of Base Burning Propulsion Using Lateral Injection

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Nomenclature

A = area
L_c = cavity length
M = Mach number
$\dot{m}_i$ = injectant mass flow rate
P = pressure
U = velocity
δ = divergence angle of annulus
ρ = density
σ = mixing half-angle
θ_c = cone half-angle
θ_w = cavity half-angle

Subscripts

∞ = freestream
b = base

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Introduction

THE use of fluid injection and combustion in the separated region behind blunt-based projectiles or vehicles has been a matter of interest ever since it became known that the base pressure could be raised by this means. Some of the early work is listed in Refs. 1-3. However, base pressures significantly above ambient values have proved difficult to reach, as can be seen by considering the most recent experimental program[4] in this area, in which base pressure ratios greater than 1 were obtained only at the cost of some questions of tunnel interference, and none greater than 2 were obtained at all.

Higher base pressure ratios may be accessible as a result of the concept developed by Strahle[2]; and other, more easily implemented methods of achieving high performance, such as the one discussed in this Note, may also exist.

Analysis

A model of base burning propulsion can be developed by modifying existing base flow methods to include the effects of injection. The Crocco-Lees and Korst-Chapman approaches have been the subjects of such modification,[5,6] but results have not been entirely satisfactory, due partly to the nontrivial problems involved in treating axial symmetry, and partly to the complexity of these methods, when regions of different fluids must be distinguished.

Another approach is to develop an analysis directly for the base burning case. This was done by Schetz et al. for base bleed only[7] and then extended to include lateral injection.[8] The model used accounts for many important features of the flow, including downstream mixing and coupling of the viscous wake flow with the inviscid surrounding flow. The model provides an interesting insight into the case of a high Mach number flow of low static temperature, but high stagnation temperature, when there is a question whether chemical reaction heats or cools the flow.

However, the model of Schetz et al. has limitations that make it less useful for lateral injection. As it stands, it does not treat the injection process in any detail. Further, in the near wake region, it appears to treat the cavity and the surrounding shear layer as a single one-dimensional (radially averaged) flow. Although this is a good assumption for massive base bleed, it is probably not as good for lateral injection.

The present work is an attempt to improve the treatment of lateral injection by using existing, detailed computer models of reactive liquid and gas injection (for the liquid injection case, see Ref. 9), combined into a code we refer to as BBLIP (for Base Burning/Lateral Injection Propulsion). In the component models, the injectant turns from its original direction and moves downstream in a central region surrounding by a shock layer. These regions are calculated stepwise downstream, with the central region expanding by mixing and combustion, and with pressure and direction equalized across the dividing streamline between the central region and the shock layer. Combustion is controlled by mixing for the case of a gas jet, and for a liquid jet by jet breakup, evaporation, and mixing.

At the base plane, the individual nozzle flows are transformed to a single annulus concentric with the body and axially symmetric, and the inner boundary of this annulus turns inward as shown in Fig. 1 to an angle θ_w. The inner boundary pressure presently is calculated using a simplified recirculation model, which includes a term accounting for the addition of base bleed, and thus allows evaluation of the possibly synergistic effect of combining base bleed and lateral injection. The outer boundary pressure is calculated from expansion of the outer flow through an angle $\theta_c + \theta_w - \delta$, where θ_c is the cone half-angle and δ is the divergence angle between inner and outer annulus boundaries. Note that because of axial symmetry, in general $\delta > 0$ even if the annulus flow is taken as frozen and without mixing. The streamwise

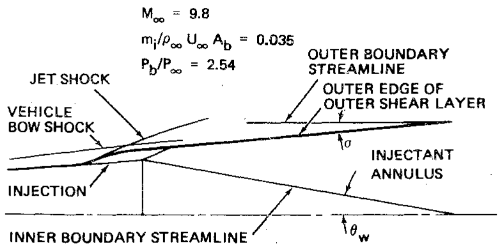

Fig. 1 Injectant annulus for base burning propulsion using lateral injection; geometry approximately to scale.

development of the injectant annulus is calculated using equilibrium chemistry, in zones of varying concentration, to prevent losing, via cross-stream averaging, the highly nonlinear effect of concentration on heat release. Conservation of mass and momentum in the injectant annulus also is required.

Entrainment of air is accounted for via the angle σ (Fig. 1), which is considered to be unknown, to be determined by comparing program predictions with the results of experiments. The external shear layer somewhat resembles the shear layer bounding a coaxial jet, for which data exist that could be used to calculate σ. It is likely, however, that the mixing half-angle of the external shear layer will depend on the geometry at the injectors where that shear layer originates, and therefore σ is preserved as an unknown.

In calculating base pressure, normal pressure gradients in the injectant annulus are assumed negligible. The calculation advances as follows. First, θ_w is chosen. Second, δ is varied until $P_{exit} = \frac{1}{2}\ (P_{outer} + P_{inner})$. Then a new θ_w is chosen and the process is repeated until $\epsilon = (P_{outer} - P_{inner})/P_{outer}$ meets a preset criterion. The resulting pressure is the desired solution.

Results

Results are shown for a 6-deg half-angle cone vehicle at a flight Mach number of 9.8, using a fuel-rich, nonaluminized solid propellant exhaust as the injectant. The dimensionless injectant mass flow rate is $\dot{m}_i/\rho_\infty U_\infty A_b = 0.035$. These parameters are based on the application in mind here, which is to interceptors, and to the imminence of shock-tunnel tests under these conditions.[10]

The geometry of the resulting flow is shown approximately to scale, for the case of combustion and for $\sigma = 6°$ in Fig. 1. Figure 2 shows calculated geometry and performance, including effects of mixing and of combustion. Reasonable geometries are obtained. It is interesting to observe that the inclusion of combustion shortens the cavity whereas improved mixing lengthens it.

It is perhaps even more interesting, although not unexpected, that base pressure increases substantially for increased mixing. This leads us to think of methods to increase mixing; one method might be to skew the centerline of alternate nozzles about the vehicle so that any two adjacent nozzles, considered as a pair, would produce a vortical exhaust stream. It also may be, of course, that the mixing half-angle is greater than 6 deg anyway; that value is reasonably appropriate for

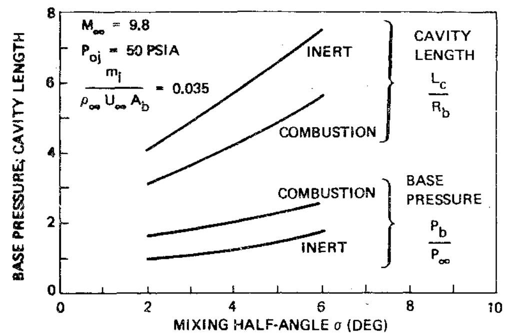

Fig. 2 Predicted cavity geometry and base pressure for various mixing half-angles.

coflowing jets, but transverse jets mix faster, and the jets making up the injectant annulus may retain enough memory of their transverse origins (in the form of the usual vortex pair in each) to result in greater mixing. In any case, we see some unexpected possibilities for performance optimization.

Acknowledgments

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