Accurate prediction of rocket exhaust plume shape and properties is vital because upstream surface pressures depend on the plume characteristics, even in supersonic flow. Under-expanded plumes, in particular, can result in a bow shock in the region of the solid body, thus drastically altering surface pressure and velocity and affecting calculated lift and drag forces and moments. Rather than perform countless experiments or a set of plenum-to-plume hot-flow calculations, costly and approximate due to combustion modeling, an ideal setup would encompass the implementation of a set of boundary conditions applied at specific boundary face surfaces (creation of a virtual plenum) that lead to accurate plume characteristics and shape in a cold flow simulation.

The work presented here examines the effect of the location (throat/nozzle/etc.) of this boundary surface on the plume characteristics and resulting rocket surface pressure distribution. Cold flow (perfect gas) simulation results are compared to experimental cold flow results (discussed in the next section) to validate this technique for use in hot flow calculations.

Previous Work

An experimental cold flow rocket plume investigation performed by Burt (1971) gives surface pressure distributions over a plume simulator for various stagnation freestream pressure ratios. The geometry includes a tangent ogive nose attached to a cylindrical body (amounting to a total length of 32.5 in with diameter 2.5 in) mounted on a swept strutting support. The conical nosel geometry is also shown. Nineteen pressure orifices were used on the surface of the missile at locations ranging from 0.0625 to 9.1875 in from the exit plane. The current study performed simulations for both over- and under-expanded conditions to compare with the experimental study: $M_e = 0.9$ with $P_e/P_\infty = 88$, and $M_e = 1.2$ with $P_e/P_\infty = 150.6$, both at 0° angle of attack.

A study by Pandya et al. (2004) validating plume modeling through applied power boundary conditions shows that application at a plenum location leads to accurate surface pressure distributions for a range of pressure ratios and Mach numbers. The current study differs in that several locations were tested in order to determine whether a post-throat location could possibly lead to the same agreement with experimental data.

Analysis & Conclusions

The aim of this study was to determine whether there exists a post-plenum location for power boundary condition application that would result in accurate plume properties and shape, thus leading to an accurate surface pressure distribution. Looking at the pressure distribution over the aft-body for $M_e = 0.9$, it is clear that for cold-flows locating the BCs in the plenum region leads to the most accurate results when compared to experimental data; however, a post-throat location is preferred for hot flow calculations as combustion continues through the throat and nozzle. The Mach contours, wake survey plots, and surface pressure indicate that the plume properties for the throat run are most consistent with those of the plenum run.

A look at the physical flow through a nozzle sheds some light on the poor results when boundary conditions are placed in the diverging section of the nozzle. Because flow always must be parallel to the boundary/nozzle walls, the gas flowing through the throat will always be uniformly horizontal. However, this means that a vertical velocity component must exist in the diverging nozzle section. In flow calculations, the simulated flow comes out uniformly in the horizontal direction, perpendicular to the boundary planes; thus only the simulated flow in the throat and plenum cases is being introduced into the model in the same direction as a naturally occurring flow. The result is that the flow in the diverging nozzle cases must expand (Prandtl-Meyer expansion fan) such that it follows the nozzle wall. This effect can be seen in the wake surveys; the constant-property sections in the center of the plume at the exit-cuts (obvious in the 1.2 and 1.4 nozzle cases) are a result of the BC-set plug flow not yet having passed through the expansion fan.

The differing surface pressures at $M_e = 1.2$ are a result of the inviscid simulation being unable to model the pressure information being fed upstream through the subsonic boundary layer. Thus the simulation results, as compared to the experiment, show a much larger pressure jump due to the shock; however, the integral of pressure would result in similar hard-body forces for each case. Just as in the $M_e = 0.9$ case, surface pressures and Mach contours show the plenum and throat locations giving almost identical results.

In conclusion, boundary conditions applied at a surface plane at or just aft of the nozzle throat give accurate plume shapes and characteristics, and will give a good indication of surface pressure.

References
