Investigation of the Ram Accelerator Projectile In-tube Stability

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Introduction

Analytical and numerical computations of the aerodynamic forces on ram accelerator projectiles operating in the thermally choked propulsive mode are being carried out to investigate their in-tube stability characteristics. The ram accelerator is a hypervelocity launcher that uses a ramjet-like propulsive cycle to generate thrust for sub-caliber projectiles as illustrated in Fig. 1 (Hertzberg et al., 1988). Fins or tube rails have been used in experiments to keep the projectile centered as it accelerates through the (Bruckner et al., 1991, Sasoh et al., 1998, Giraud et al., 1998, Seiler et al., 1998 and Chang et al., 1998). Small perturbations to the projectile orientation (canting and/or translation) result in a pressure imbalance which produces both a side force and torque (Li et al., 1996). In the case of projectiles having fins, these aerodynamic forces on the projectile are counteracted by the reactions of the fins on tube walls. Erosion induced by high-speed fin/tube wall friction eventually wears the fins down which leads to increased canting and further distortions to the pressure field (Hinkey et al., 1993 and Giraud et al., 1998). Ultimately the projectile is canted so far to one side that the corresponding minimum flow passage area (i.e., throat area) becomes too small to accept the required mass flow and an unstart occurs. The purpose of this investigation is to determine the magnitude of the destabilizing forces arising from the translation and canting of two-dimensional and axisymmetric projectiles. These results could facilitate designing functional projectiles that are aerodynamically stable in the reactive flow field of the thermally choked ram accelerator, thus minimizing the need for fins.

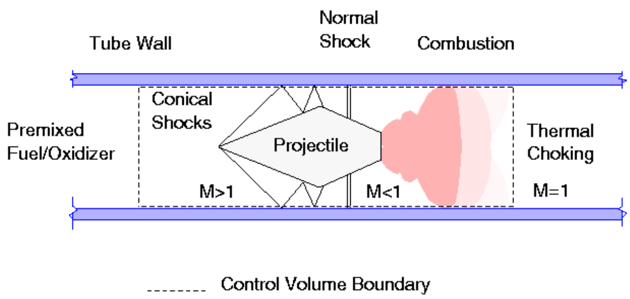


Fig. 1. Thermally choked ram accelerator propulsive mode.

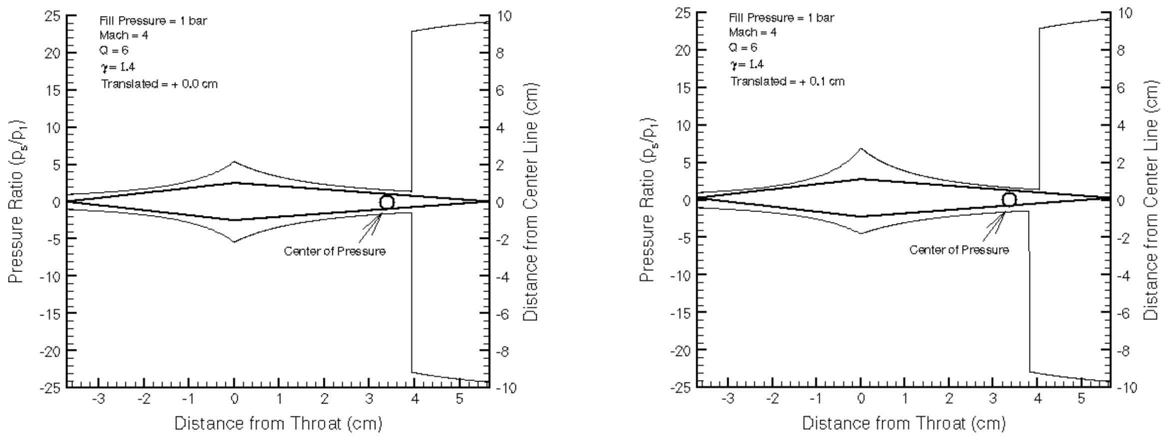
A schematic of the thermally choked ram accelerator propulsive mode flow field, presented in the reference frame of the projectile, is shown in Fig. 1. Even though the ram accelerator flow field is inherently unsteady due to projectile acceleration, reasonable estimates of the forces on the projectile can be determined while assuming quasi-steady flow (Bruckner et al., 1991). The supersonic propellant is decelerated over the fore-body of the projectile before it passes through the minimum flow passage area, or throat, afterwhich the flow expands over the diverging aft-body until it passes through a normal shock wave. The shocked flow then decelerates as it subsonically expands back to full tube area. Subsonic combustion occurs directly behind the projectile and the flow is subsequently thermally choked. This choking of the flow stabilizes the normal shock wave, which in reality is a complex system of interacting shock waves, on the aft-body of the projectile. As the projectile accelerates, the normal shock falls back on the body until eventually it reaches the base tip of the projectile. At this point thrust equals drag and, in principle, the projectile has reached a peak velocity equal to that of the Chapman-Jouguet detonation speed of the propellant (Knowlen and Bruckner, 1992).

Analytical One-dimensional Modeling

The combustion process is modeled as subsonic heat addition in a constant area duct leading to thermal choking of the flow. In the ideal model of the thermally choked propulsive mode, the duct flow is isentropic everywhere except across the normal shock wave and in the heat addition region. For the purposes of this study, the propellant is assumed to have a constant specific heat ratio ($\gamma = 1.4$) and the non-dimensional heat release (combustion heat release normalized to the product of the propellant initial temperature and constant pressure specific heat capacity) is assumed to be $Q = 6$. The shock position in the flow channels is determined by an iteration process which finds the appropriate flow area ratio for a normal shock such that the subsonic flow meets the boundary condition of the base pressure prescribed by the thermal choking of the flow.

The pressure distributions for centered, translated, and canted two-dimensional projectiles are determined for a bi-wedge configuration having a nose wedge half-angle of 15^{o} and a body wedge half-angle of 10^{o}. The projectile throat is 2 cm wide and the tube width is 3 cm. A reference origin is placed on the centerline of the tube and at the projectile throat, as indicated by the projectile schematics in Fig. 2. Only a centered and a translated projectile are shown here. The static pressure ratio distribution (static pressure normalized to fill pressure) for the ideal thermally choked propulsive mode on the top and bottom of a centered projectile at $M = 4$ is shown in Fig. 2a. The net horizontal and vertical forces on the projectile and the net moment are determined from these pressure distributions. The center of pressure for the projectile is indicated with a circular plotting symbol.

When the flow area profile is altered by only the translation of the projectile centerline, the pressure distribution becomes unbalanced and finite torque is generated. The pressure distribution of a projectile translated upward by 1 mm is shown in Fig. 2b. The lower side has the least flow contraction at the throat and thus the least ram pressure build up; however, the normal shock wave moves up on the projectile. Conversely, the ram pressure at the throat is higher in the upper flow passage and the normal shock is farther back. A net torque is produced which moves the center of pressure off the projectile centerline, as indicated in Fig. 2b.



(a) (b)

Fig. 2 Pressure distribution on upper and lower surfaces of bi-wedge projectile at $M = 4$.
a) centered; b) translated vertically by +0.1 cm

The movement of the center of pressure (*cp*) is plotted in Fig. 3 for both the centered and translated projectiles as they are accelerated from Mach 3 to 5.5 in a propellant having a specific heat ratio of $\gamma = 1.4$, and a non-dimensional heat release of $Q = 6$. The horizontal position of the *cp* moves backwards for both the centered and translated cases as the projectile gains velocity until it reaches Mach ~ 4.5, after which the *cp* moves forward. As expected for a centered projectile, the vertical coordinate of the *cp* remains on the centerline. In the translated case, the *cp* moves above the tube centerline as a result of torques induced by pressure imbalances. The net effect of the translated pressure field is to cause the nose tip to pitch upward.

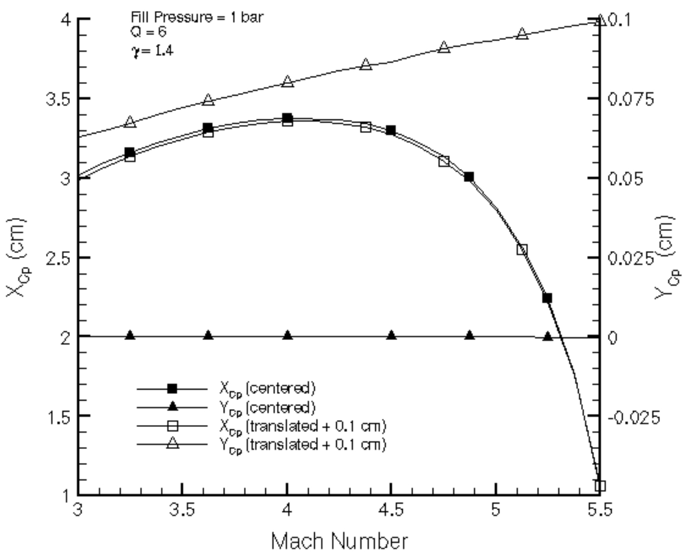


Fig. 3 Center of pressure motion for centered and translated projectiles as function of Mach.

Computational Fluid Dynamics Modeling

The two-dimensional analysis highlights the general stability characteristics of a simplified projectile geometry that is being ram accelerated through a tube. To determine the stability behavior of a canted axisymmetric projectile, the three-dimensional Navier-Stokes equations are solved with finite difference method and LU-SGS approach. The non-oscillation, Non-free-parameter, Dissipative scheme (NND scheme, a kind of TVD scheme) is used to discretize the convection terms on a 172×41×41 mesh. The supersonic flow field around a 29 mm-diameter projectile (axisymmetric) having a 10^{o} nose cone and 5^{o} body angle in a 38-mm-bore tube is determined at Mach 4 with a canting angle of 4^{o}, as shown in Fig. 4. At this point in time, only the supersonic flow field is being considered in the computations, thus the projectile is actually decelerating under these conditions. The integration of aerodynamic forces shows that the axisymmetric projectile is statically stable if the center of gravity is ahead of the center the center of pressure, and it becomes more stable if the center of gravity moves toward projectile's nose-tip. This solution pertains to supersonically coasting projectiles, however, the results are expected to be quite different once the motion of the normal shock wave on the body is considered.

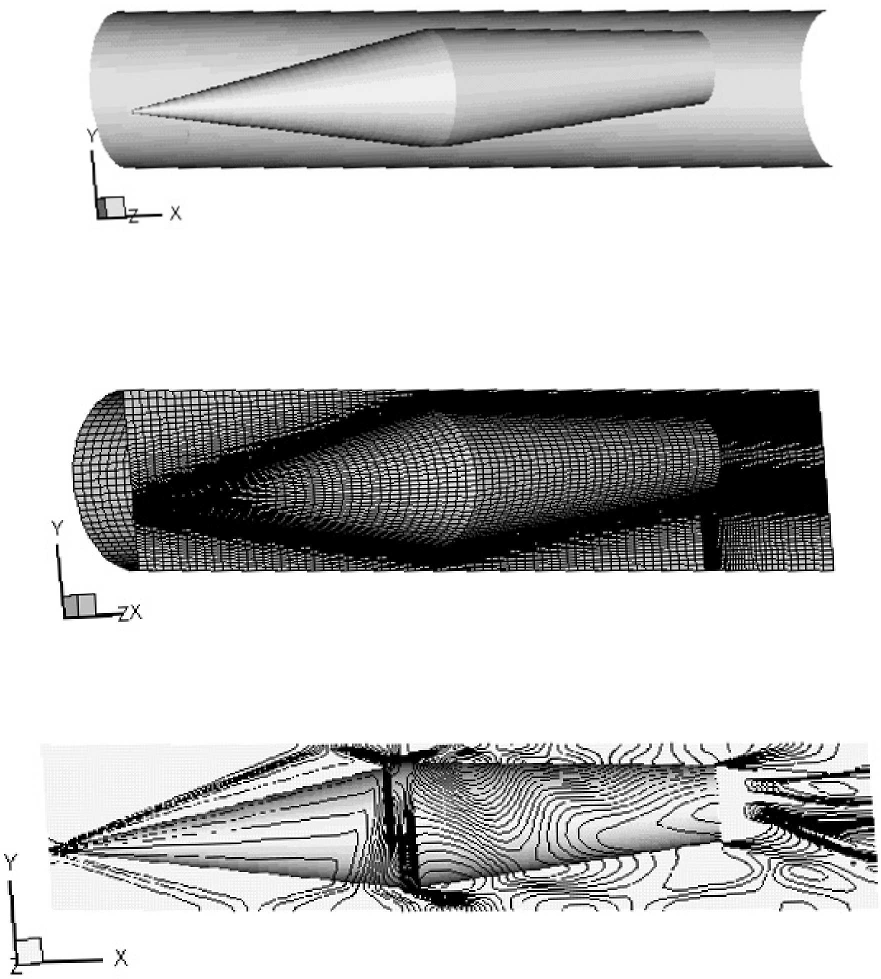


Fig. 4 Computation of canted projectile pressure distribution in unreactive Mach 4 flow.

Summary

Ongoing efforts are underway to incorporate the influence of the normal shock motion due to canting and changes in Mach number in the numerical computations. Analytical calculations for projectiles that are both translated and canted are also in progress. The results of these investigations will determine the degree of static stability that is realized by the placement of the projectile center of gravity over a range of canting angles as the projectile accelerates in the thermally choked propulsive mode. The ultimate goal is to design functional aerodynamically stable projectiles that will need very little external support (i.e., fins or rails) to remain centered while being launched by a ram accelerator.

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