Gasdynamic Operation of Baffled Tube Ram Accelerator in Highly Energetic Mixtures

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Introduction

The ram accelerator is a chemical mass driver that accelerates sub-caliber projectiles with ramjet-like propulsion cycles through a smooth-bore tube filled with gaseous propellant (Hertzberg et al., 1988). The ability of the ram accelerator to provide nearly constant thrust at velocities greater than 3 km/s and the relative ease of its scalability have made it one of the most promising hypervelocity launcher concepts for direct space launch and military defense applications (Knowlen and Bruckner, 2001). The development of the ram accelerator, however, is not without challenges. The three main issues that reduce the efficacy of this concept are:

1) It has been empirically determined that the heat release of the propellant must be reduced to ~1/3 of that which is available to effect stable ram accelerator operation, which limits the peak thrust to ~1/3 of the theoretical maximum. Using a propellant with a greater heat release results in the undesirable situation in which the driving combustion wave surges past the projectile, causing a diffuser "unstart" (Higgins et al., 1998). In addition, the unstart phenomena also limits the lowest velocity at which the ram accelerator process can be initiated (Mach 2.5 or 0.7 km/s), which puts a much bigger onus on the muzzle velocity capability of the pre-launcher for applications that require massive projectiles (Knowlen et al., 2000).

2) In order to realize high acceleration performance with massive projectiles using proven propellants, the fill pressure has to be increased to the point where its density begins to approach that of liquid water (Bundy et al., 2000). The peak pressure of the ram accelerator propulsive cycle, however, is often 10-20 times the fill pressure, which puts a significant burden on the projectile and launch tube design under these circumstances.

3) The peak velocity obtainable while operating the ram accelerator in the thermally choked propulsive mode is significantly reduced by the presence of fins in the throat region (the throat is the point of maximum projectile cross-section). It has also been shown that the peak operating velocity with rail-stabilized, axisymmetric projectiles is similarly reduced (Seiler et al. 2000). These empirical results indicate that the ram accelerator propulsive cycle is very sensitive to the presence of flow disturbances within the throat region, thus the potential of accelerating axisymmetric projectiles with the thermally choked propulsive mode at high enough velocity to effect super-detonative ram accelerator operation does not appear promising. Conversely, the acceleration of finned-projectiles in the velocity range of 3-8 km/s with the super-detonative ram accelerator propulsive mode puts a severe aero-thermal loading burden on the stabilizing fins (Knowlen et al., 1996).

Baffled-Tube Concept

All of the deficiencies of the ram accelerator discussed above can be addressed by the novel concept of using baffles on the wall of the tube, as shown in Figs. 1 and 2. Baffles, or annular rings, attached to and/or machined into the tube wall act to isolate the combustion process behind the projectile from the intake of unburned propellant past the conical nose of the projectile. This isolating effect allows more highly energetic mixtures to be used without the risk of the combustion

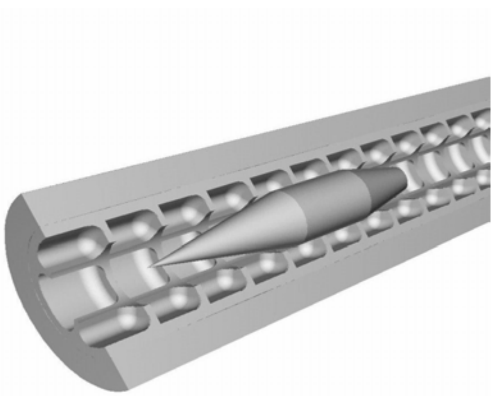

Figure 1. Cut-away view of baffled tube with axisymmetric projectile.

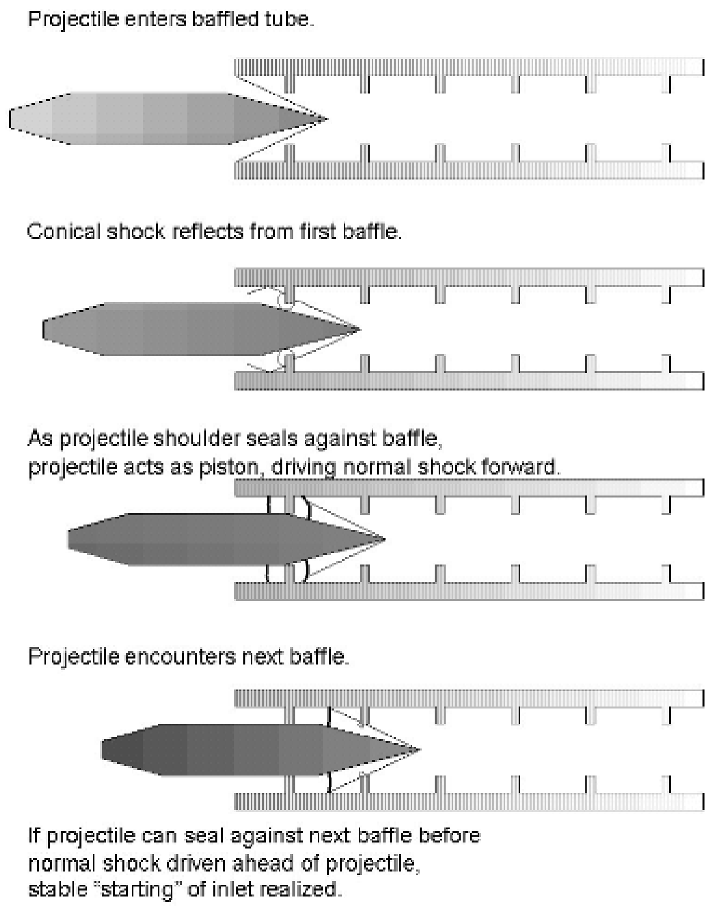

Figure 2. Schematic of flow field as projectile enters baffled tube.

driving a shock wave ahead of the projectile throat, causing an unstart. Since the baffles act to contain the combustion behind the projectile, the tube-to-projectile-throat area ratio can be increased, allowing successful starting of the ram accelerator at as low as Mach 2 without danger of unstart. The use of more energetic propellant, a greater tube area, and operation at lower Mach number all act to increase the thrust on the projectile, thus greatly increasing muzzle velocity without having to increase propellant fill pressure. In addition, the projectile now rides on the rails and baffles of the ram accelerator tube wall, eliminating the need of fins to center the projectile during operation in the thermally choked propulsive mode. As a result, an axisymmetric full-bore (with respect to the pre-launcher) projectile can now be used which is the preferred geometry for super-detonative ram accelerator hyper-velocity applications (Seiler et al. 1998). In addition, the projectile aero-thermal heating issues are significantly reduced, for a given acceleration level, when utilizing more energetic propellant, rather than increasing fill pressure to boost ram accelerator performance.

The baffles have a hole bored through their centers that is just large enough to allow the passage of the projectile. The spacing of the baffles is such that the cylindrical mid-body of the projectile will completely span at least two baffles at any time. This forms a sequential series of propellant chambers down the bore of the tube, as shown in Fig. 2. The propellant is initially ignited behind the projectile and the combustion process drives a pressure wave system up its base and into the annular chamber around the mid-body. The baffles act as a one-way valve in which propellant can be ingested by the supersonic diffuser of the projectile, yet the combustion-driven pressure wave system cannot be pushed ahead of it. Consequently, the propellants can be formulated to be as energetic as possible to maximize acceleration. As the projectile velocity increases, the intensity of the shock waves and corresponding increase of propellant temperature within the annular chamber increases to the point where it is possible for the combustion to reach completion before the products expand back to full tube area. The ultimate velocity limitation of this concept is when the strength of the precursor shock wave, generated by the leading edge of the projectile shoulder as it just enters the baffle, is sufficient to directly initiate a detonation wave that can travel through the next baffle before the projectile shoulder seals it. The induction time of shock-induced detonation is strongly dependent on both the strength of the shock wave and duration time of its presence. Thus, the thickness of the baffles, their spacing, and the volume of the expansion chamber all play a significant role in the application of this concept.

Experimental Apparatus and Results

A schematic of the one-meter-long baffled-tube in which exploratory experiments were carried out is shown in Fig. 3. The diameter of the hole bored through the baffles was 38.1 mm and the inner diameter of each annular chamber was 63.2 mm. The baffle thickness and spacing for this configuration were 3.2 mm and 28.6 mm, respectively. The multiplicity of chambers was formed by stacking individual inserts within a one-meter-long tube having an inner diameter of 76.2 mm. Axisymmetric projectiles of various geometries were shot through this test section with a light gas gun at velocities ranging from 1-1.3 km/s. The primary purpose of these experiments was to determine if the baffle-rail configuration was appropriate for stabilizing the projectile while enabling it to remain “started” in pressurized, inert gases. These experiments demonstrated that the projectile would remain started under these conditions.

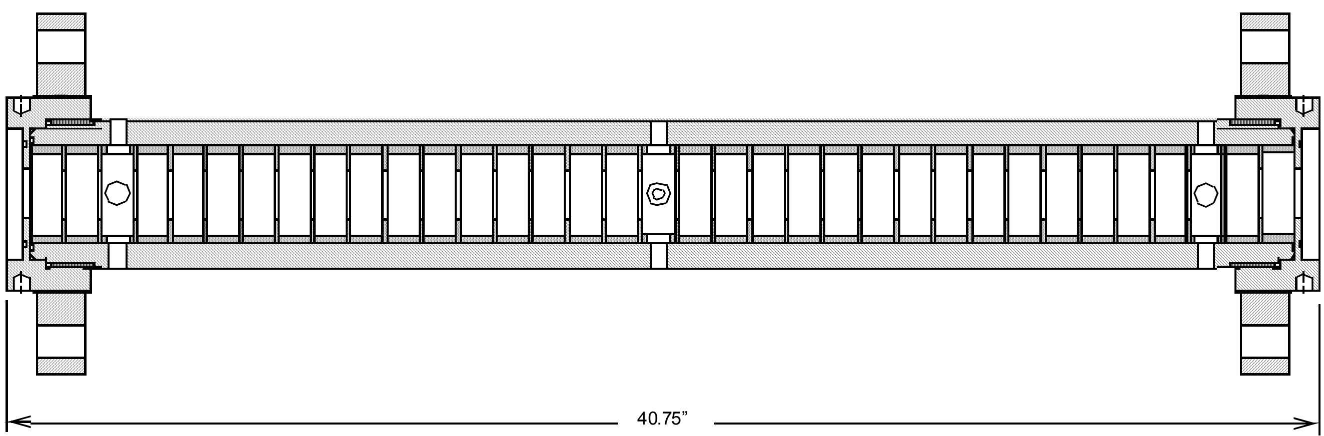

Figure 3. Baffled tube test section for 38-mm diameter projectile.

The second part of this experimental program was to determine if propellant ignition could occur when the projectile propagated into a reactive atmosphere with greater sensitivity than has been demonstrated in conventional ram accelerators in the same velocity range. These experiments were also successful, however, the measured accelerations were less than anticipated. Results of several experiments are shown in Fig. 4. Experiment number HS1647 demonstrated an 80 m/s velocity gain in the baffled tube when using a propellant consisting of 2.7CH4+2O2 at ~24 bar fill pressure. Low acceleration performance (in the context of the thermally choked ram accelerator propulsive mode) during the starting process is typical, thus, does not necessarily imply a conceptual failure. Indeed, the ease and simplicity in which combustion was initiated without the presence of an obturator are quite encouraging; and ram accelerator operation was demonstrated in a propellant that was twice as energetic as ever successfully used before.

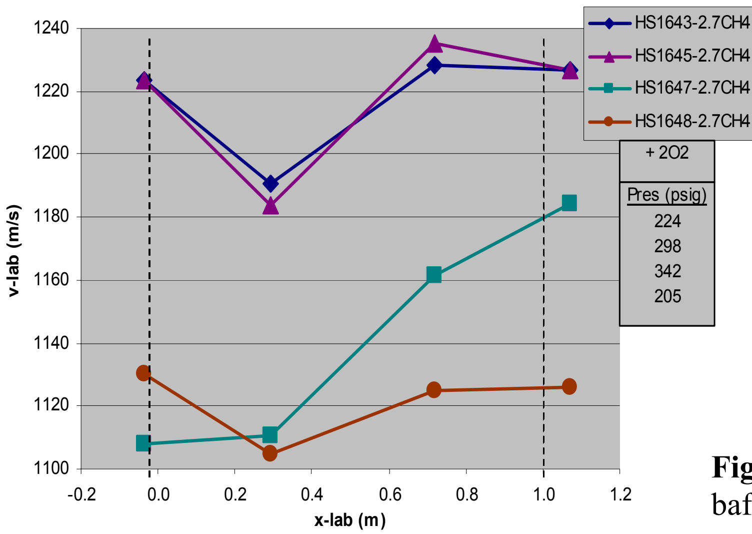

Figure 4. Velocity-distance data from baffled-tube experiments.

Conclusion

A novel baffled-tube concept for enabling unlimited energy addition behind the ram accelerator projectile has been proposed and tested. Experiments have shown that the projectile is able to pass through the baffles at supersonic velocity without generating an unstart. Combustion was successfully initiated behind an axisymmetric, full-bore projectile that was launched without an obturator. Positive acceleration has been demonstrated.

References

Bundy C, Knowlen C, Bruckner AP 2000 "Ram Accelerator Operating Characteristics at Elevated Fill Pressures" *J. Physique IV* 10: Pr11 11-21.

Hertzberg A, Bruckner AP, Bogdanoff, DW 1988 "Ram Accelerator: A New Chemical Method for Accelerating Projectiles to Ultrahigh Velocities" *AIAA J* 26:195-203.

Higgins AJ, Knowlen C, Bruckner AP 1998 "Ram Accelerator Operating Limits, Part 1: Identification of Limits" *J Propulsion and Power* 14: 951-958.

Knowlen C, Higgins AJ, Bruckner AP, Bauer P 1996 "Ram Accelerator Operation in the Superdetonative Velocity Regime" AIAA Paper 96-0098.

Knowlen C, Bundy C, Bruckner A, Kruczynski D 2000 "Investigation of Obturator and Ignitor Effects on Low Velocity Starting of the Ram Accelerator" *J de Physique IV* 10: Pr11 49-58.

Knowlen, C., Bruckner, A.P. 2001 "Direct Space Launch Using Ram Accelerator Technology," STAIF 2001, M.S. El-Genk (ed), American Institute of Physics, Springer-Verlag, New York, pp.583-588.

Seiler F, Patz G, Smeets G, Srulijes J 1998 "Presentation of the Rail Tube Version II of ISL's RAMAC 30" *Ram Accelerator* Takayama K, Sasoh A (ed.) Springer-Verlag, Heidelberg, pp. 79-87.

Seiler F, Patz G, Smeets G, Srulijes J 2000 "Progress of Ram Acceleration with ISL's RAMAC 30" *J. de Physique IV* 10: Pr11 31-40.