Baffled-Tube Ram Accelerator Operation with Methane-Air Propellant

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1 Introduction

The baffled-tube ram accelerator (BTRA) is a device for accelerating axisymmetric projectiles through a tube utilizing gaseous combustible mixtures. The BTRA consists of a series of washer-like baffles with rails in between them to provide structural rigidity, as shown in Fig. 1. The internal baffles prevent combustion-driven pressure pulses from moving ahead of the projectile in energetic propellants. This means of in-tube propulsion differs from conventional smooth-bore ram accelerators (SBRA) in that the projectile does not need fins to keep it centered in the tube and the propellant can, in principle, be more than twice as energetic without causing unstarts [1]. Furthermore, the projectile length and diameter are scalable to large bore diameter, e.g., 1-m-bore, the acceleration is adjustable via fill pressure and propellant chemistry, and the theoretical maximum velocity is approximately 3 km/s. Thus, the BTRA by itself can readily replace the first stage of a multi-staged rocket system to increase payload mass fraction significantly and lower costs for launch-to-orbit applications. Presented here are the results of experiments with methane-air propellant utilizing flat-faced baffles in a 38-mm-bore test apparatus.

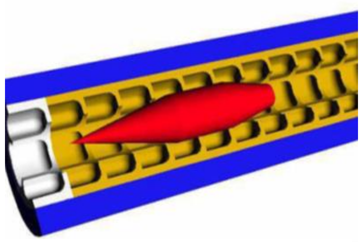

Figure 1 Baffled-tube ram accelerator configuration.

2 Background

In general, the ram accelerator utilizes ramjet-like propulsion cycles to accelerate projectiles through a tube filled with pre-mixed propellant [2]. At velocities below the Chapman-Jouguet (CJ) speed of the propellant, a combustion process that is subsonic with respect to the projectile is stabilized behind it with the flow thermally choked at full tube area (Fig. 2). Theoretically, this self-synchronized combustion zone maintains high base pressure on the projectile that accelerates it up to the CJ speed of the propellant [3]. The thrust increases with increasing heat release and decreases with increasing Mach number. In practice, it has been found in SBRA experiments with the thermally

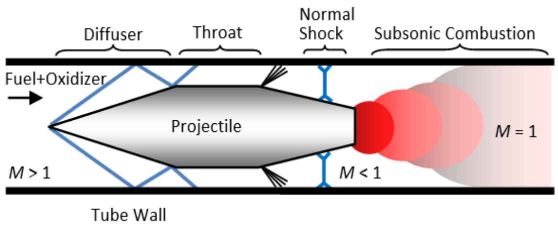

Figure 2 Thermally choked ram accelerator propulsive mode.

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choked propulsive mode that stoichiometric propellant must be diluted with inert gases to reduce the heat release of combustion by 60%-70% to enable robust operation at in-tube Mach numbers up to $M = 5$. Nonetheless, even with the heat release being reduced by more than half that which is available, the smooth bore ram accelerator has demonstrated thrust levels greater than 440 km/s^2 [4,5].

To increase the thermally choked ram accelerator thrust at a given fill pressure and Mach number, the propellant heat release must be increased. A means to enable operation with very energetic propellant that utilizes a series of baffles inserted inside a smooth bore tube has proven to be effective in this regard [1]. The baffles form a series of chambers and block the combustion driven pressure pulses from propagating ahead of the projectile (Fig. 3). Furthermore, as the projectile passes through the passageway in each baffle it unstarts and generates a normal shock that attenuates as it expands radially, which allows the projectile to overtake it and "re-start" before its shoulder passes through the chamber. This enables fresh propellant to be ram-compressed in the annulus and subsequently burned. This ram accelerator configuration also offers the advantage of utilizing axisymmetric projectiles that do not have any intrinsic length limitations if their shoulder spans the distance between at least two adjacent baffles.

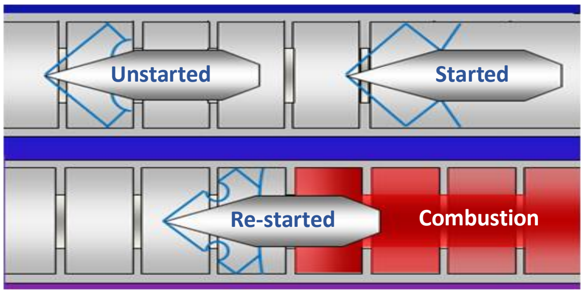

Figure 3 Baffled-tube ram accelerator flow field as projectile passes through the chambers.

3 Theory

Operation of the SBRA in the thermally choked ram accelerator propulsive mode occurs when the projectile is accelerated while below the CJ speed with a subsonic combustion process that is terminated by thermal choking at full tube area. This results in a sonic plane behind the projectile that isolates the combustion zone from downstream disturbances while stabilizing a normal shock wave on the projectile tail cone. The thrust equation for the thermally choked propulsive mode is derived by applying the conservation laws for a one-dimensional, quasi-steady flow process to the control volume shown in Fig. 4, where boundaries 1 and 2 are the entrance and exit planes, respectively. Since the thermally choked exit plane ($M_2 = 1$) is an entropy extremum, the flow phenomena inside the control volume can be neglected [6]. The resulting equation for non-dimensional thrust (thrust, F, normalized by fill pressure, P_1, and bore cross-sectional area, A_b) is:

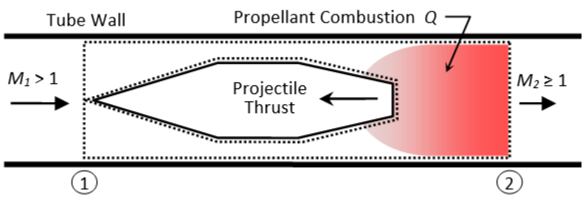

Figure 4. Control volume for one-dimensional ram accelerator thrust modeling.

$$I_{SBRA} = \frac{F}{P_1 A_b} = M_1 \frac{\gamma_1}{\gamma_2}(1+\gamma_2)\sqrt{\left(\frac{\gamma_2-1}{\gamma_1-1}\right)\frac{\frac{h_1}{c_{p1}T_1}+\frac{M_1^2(\gamma_1-1)}{2}+Q+\frac{D(\gamma_1-1)}{P_1 A_b \gamma_1}}{\frac{h_2}{c_{p2}T_2}+\frac{(\gamma_2-1)}{2}}} - (1+\gamma_1 M_1^2) - \frac{D}{P_1 A_b} \quad (1)$$

The thrust in the thermally choked ram accelerator is dependent on the in-tube Mach number, M_1, and the propellant non-dimensional heat release, Q (determined from the difference of heat of formation of the products and reactants, normalized by constant pressure specified heat capacity, c_{p1}, and static temperature, T_1, of unburned propellant). Note, D refers to baffle drag that is only present in the BTRA. For the SBRA, this drag term is neglected. The resulting thrust-Mach profile has a maximum near $M_1 \sim 2.8$ and predicts zero thrust at the M_{CJ}.

To account for the volume occupied by internal rails and baffles inside a BTRA, the baffle gas volume is equated to that of an equivalent smooth bore tube having the same amount of propellant per unit tube length, as shown in Fig. 5 [1]. The rail volume, V_{solid}, is subtracted from the chamber gas volume, V_c, and baffle bore volume, V_b. The effective tube diameter, d_{eff}, is then determined for a segment equal to the length of the chamber plus the baffle thickness. This leads to the following expression for geometric volume factor, β, and its application to the non-dimensional thrust for SBRA to provide theoretical thrust for the BTRA:

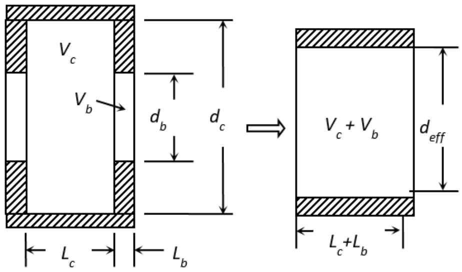

Figure 5. Effective diameter geometry for BTRA chamber.

$$\beta = \frac{A_{eff}}{A_b} = \frac{V_c + V_b - V_{solid}}{V_b\left(1 + L_c/L_b\right)} = \frac{d_{eff}^2}{d_b^2} \qquad \rightarrow \qquad I_{BTRA} = \frac{I_{SBRA}}{\beta} \tag{2}$$

The effective chamber-to-baffle bore area ratio, β, in principle, determines the minimum entrance Mach number for BTRA operation. This corresponds to the entrance Mach number resulting in sonic flow with respect to the projectile, in the annular region around its shoulder, assuming isentropic compression. The isentropic compressible flow equation relating Mach number, specific heat ratio, and area ratio for choked flow provides an estimate of the minimum entrance velocity for a given propellant and BTRA configuration.

4 Experimental Facility

The ram accelerator facility has a 38-mm-bore light gas gun to launch projectiles up to 1.2 km/s. Its test section consists of eight 2-m-long tubes with 38-mm-bore. Mass flow controllers regulate propellant components to set stoichiometry. Dump tanks before and after the test section contain the helium gun gas and combustion products from each experiment. Mylar diaphragms seal the gaseous propellant in the test section and partition the tubes for staging with different propellants when desired. Data are collected with a National Instruments PXIe-1071chassis with two PXIe-6358 modules, allowing for 32 analogue input channels simultaneously sampled at 1.25 MHz.

Operating characteristics of the BTRA were investigated with two 2-m-long shell-tubes that provided an overall length of 4 m. These replaced the second and third tubes of the 38-mm smooth bore test section, which allowed tracking the projectile prior to the entrance and after the exit of the BTRA section. The inner and outer diameters of the shell tubes were 76 mm and 114 mm, respectively. There were five equally spaced instrument port pairs in each tube for electromagnetic (EM) sensors that tracked the time-position history of the projectile and piezoelectric transducers (PCB 119) to observe the corresponding pressure signatures. An instrumented insert having a 76-mm-bore was sandwiched at the junction between the two shell tubes, as shown in Fig. 6. Thus, there were 11 instrument stations in the BTRA test section for these experiments. End caps threaded onto the entrance and exit of the shell tube compress the baffle inserts and provide a surface for the closure seals.

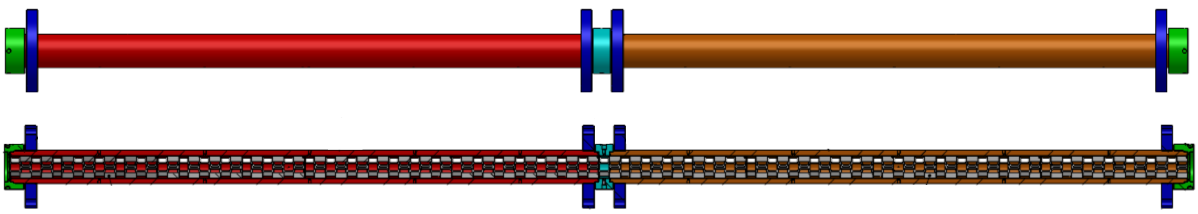

Figure 6. Shell tubes with precision bores can accommodate baffles with different geometries.

5 Baffled-Tube Insert Geometries

Described here are two different baffled tube designs with flat-faced baffles. The first design (referenced as BTRA100) had 90° baffles (normal to the flow) with open-walled side chambers (Fig. 7-left). Consequently, these inserts had the shell tube inner surface as its chamber outer wall (76-mm-chamber diameter). This resulted in the maximum chamber-to-baffle-bore area ratio for these experiments. These inserts were fabricated in 6, 7, and 8 chamber units, with each baffle chamber clocked 45° so that rails would always support the mid-span of the baffles. This enabled support for the maximum pressure differential across the baffles and allowed thinner baffles (3.8-mm-thick) to be used for a given fill pressure. Through testing, however, it was found that at moderate fill pressure (i.e., 2 MPa) the loads transmitted through the rails from multiple upstream baffles plastically deformed the baffles at the exit of the tube. Thus, the maximum operable pressure with these inserts was limited to 1.4 MPa to prevent deformation of the inserts [7].

In order to test the BTRA at higher fill pressures, a new baffle design (BTRA500) was utilized that had baffles oriented normal to the flow with fully enclosed baffle chambers (64-mm-chamber diameter) and aligned rails. The baffle thickness was 6.4 mm, and the chambers were 29.4-mm-long. Fabricating these inserts in single chamber sections, resulted in 56 units used per 2-m-long shell tube. They have four sidewall holes (Fig. 7-right) to enable tube wall instruments to monitor pressure phenomena and projectile time-of-passage and fill ports for the propellant. Although the net gas volume was reduced in this design, significantly higher fill pressures were possible (5 MPa rated), leading to higher overall thrust levels.

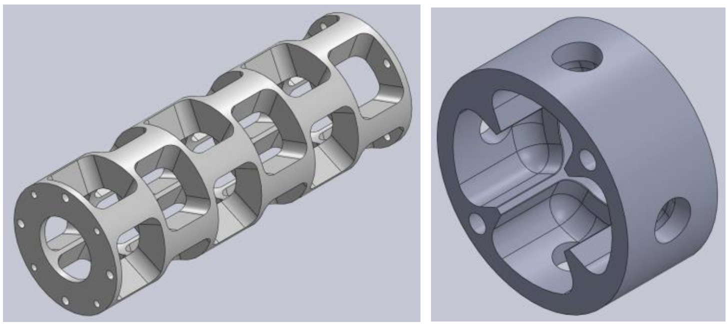

Figure 7. BTRA insert designs. Left: BTRA100 with open-walled chamber and fabricated in multiple unit-lengths. Right: BTRA500 with enclosed chamber and fabricated as individual units.

6 Projectile Design

The axisymmetric projectile design shown in Fig. 8-left was fabricated from polycarbonate for these experiments. Its shoulder diameter and length were 35 mm and 59 mm, respectively. The diametric clearance of the shoulder and baffle bore was 3 mm, which has proven to be effective over a wide range of test conditions. A threaded nylon plug retained the neodymium magnet inserted in the projectile base. An obturator with diameter of 37.4 mm (Fig. 8-right) prevented blow-by during the light gas gun launch and facilitated ignition of the propellant during the starting process. When fabricated from polycarbonate, the projectile and obturator have masses of 123 g and 23 g, respectively.

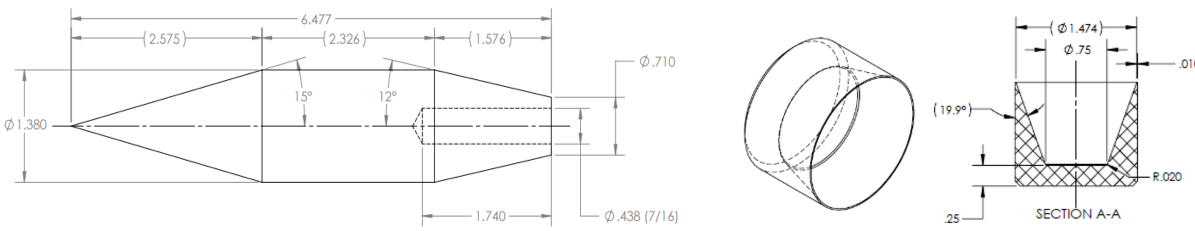

Figure 8. Drawing units in inches. Left: BTRA projectile design. Right: Obturator design.

7 Experimental Results

The BTRA configuration for the experiments reported on here had a 7-chamber BTRA100 insert at the entrance to the first 2-m-long shell tube, with BTRA500 inserts (49 units) used for the remaining length. Projectile velocity from the evacuated tube ahead of the BTRA stage was measured from EM sensor time-of-passage data. The methane-air-oxygen propellant was stoichiometric with molar ratios of $1CH_4$+$2O_2$+$4.67N_2$, which corresponds to an enriched air blend of 30%O_2-70%N_2. Prior studies have shown that reliable BTRA operation could not be maintained in this experimental configuration with greater O_2 enrichment.

Velocity-distance data from this 2-m-long BTRA stage at a fill pressure of 2.2 MPa with entrance velocities ranging from 665 m/s to 785 m/s are shown in Fig. 9-left. At entrance velocities below 680 m/s, the projectile would unstart before leaving the 2-m-long BTRA tube. At entrance velocities greater than 700 m/s, however, projectiles accelerated steadily throughout the tube with a velocity increase of approximately 235 m/s and average thrust level of 12.5 kN. With β = 2.22 for the BTRA500 inserts and γ = 1.38 for unreacted propellant, the ideal miniminum entance Mach number was 1.94, or 684 m/s. The empirical result was 2.4% greater, which indicates that the total pressure losses due to conical shocks, viscous effects, and transient phenonmena were relatively small.

The influence of propellant fill pressure on the thrust-distance profile in the 2-m-long BTRA section is shown in Fig. 9-right. Pressure was varied from 1.8 MPa to 3.2 MPa in these experiments. The velocity gain increased with increasing fill pressure with average thrusts ranging from 9.5 kN to 17 kN. Thus, the thrust increased proportionally with increasing fill pressure as expected, which implied that the projectiles were not significantly deformed nor canted during BTRA operation under these conditions.

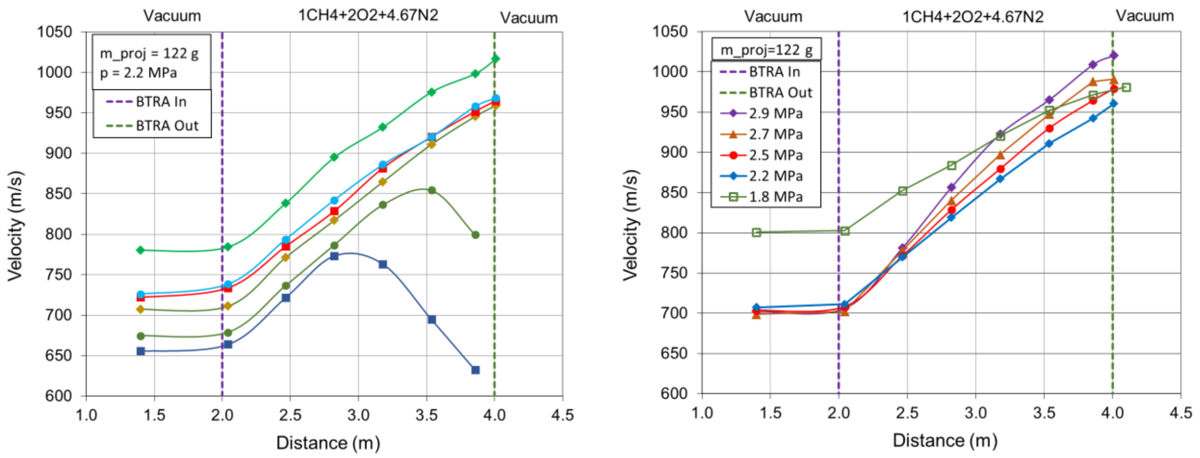

Figure 9. Velocity-distance data from 2-m-long BTRA stage. Left: Entrance velocity sweep. Right: Fill pressure sweep.

A second 2-m-long shell tube with BTRA500 inserts (56 units) added to the first enabled experimentation over a wider velocity range. Velocity was determined in the evacuated tube just after the 4-m-long BTRA stage exit with EM sensors. Shown in Fig. 10 are velocity-distance data at two different fill pressures (2.2 MPa and 2.9 MPa) and entrance velocities (790 m/s and 1040 m/s). The corresponding entrance Mach numbers were 2.23 and 2.93, respectively. Increasing fill pressure increased the velocity gain at each entrance velocity. At the lower entrance velocity, the 32% increase in fill pressure resulted in an 18% increase in average thrust. At the higher entrance velocity, the same pressure increase resulted in a 13% increase in average thrust. Note that the velocity-distance data for the first 2 m in these experiments were very similar those in the 2-m-long data presented in Fig. 8, which indicates that the thrust dropped substantially in the second 2-m-long BTRA tube section.

The non-proportional thrust increase with respect to fill pressure in the second 2-m-long BTRA tube at each entrance velocity indicates that the differences in thrust characteristics with polycarbonate projectiles were due to increased run duration and distance rather than the operation in a higher Mach number range. Deformation of the polycarbonate projectile due to in-tube aerodynamic heat transfer is a likely cause for the observed differences in thrust. Modeling of the aerodynamic heat transfer is in progress and similar experiments with aluminum alloy projectiles are planned as part of this ongoing investigation.

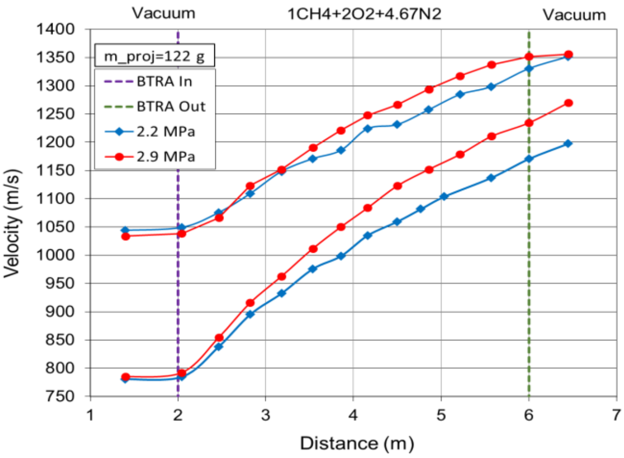

Figure 10. Velocity-distance data from 4-m-long BTRA stage.

8 Conclusion

Continuous BTRA operation with axisymmetric projectiles was demonstrated from 700 m/s to 1350 m/s (Mach 2.0 to 3.8) in CH_4 / O_2-enriched air propellant. The minimum entrance velocity was determined to be 700 m/s, which is 2.4% greater than the theoretical minimum in baffle chambers having an effective chamber-to-bore area ratio of 2.22. With polycarbonate projectiles, the thrust decreased with increasing Mach number more than predicted by theory in 4-m-long BTRA experiments. Projectile deformation due to the material softening from in-tube heat transfer accounts for this observation. These experiments have shown that the BTRA operates effectively and reliably over a relatively wide range of conditions. The upper operational Mach number limit, however, still remains to be determined.

Acknowledgements

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