Baffled Tube Ram Accelerator Combustion

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Abstract

The baffled-tube ram accelerator is a device that has the potential to accelerate axisymmetric projectiles in the velocity range of 0.5 to 3 km/s. Preliminary experiments in a 38-mm-bore device demonstrated that only about 30 to 50% of the theoretical thrust is attained using a baffle geometry that is effectively a solid washer with a center hole bored out with a slight projectile clearance. Recent transient CFD modeling results indicate that significant improvements in thrust generation capability can be realized by inclining the baffles toward the approaching projectile. With this configuration, reactive flow simulations showed that the combustion goes to completion closer to the projectile base than in the original baffle orientation, resulting in a doubling of thrust. Newly fabricated baffles based on this concept are undergoing testing. The results of these upcoming experiments with the new inclined baffle design will be presented.

1 Introduction

The baffled-tube ram accelerator (BTRA) has been under development since 2004. [1,2] This device has the potential to triple the thrust performance of the conventional smooth-bore ram accelerator (SBRA) while operating at the same fill pressure, and can reduce its minimum starting velocity (currently ~0.7 km/s) by at least 25%. Its low starting velocity ability allows for the consideration of a wide range of pre-launcher technologies for many applications, which may greatly reduce overall cost and operational complexities of these mass driver systems. Thus, the BTRA offers a significant advancement in ram accelerator technology for hypervelocity applications where axisymmetric projectiles are preferred.

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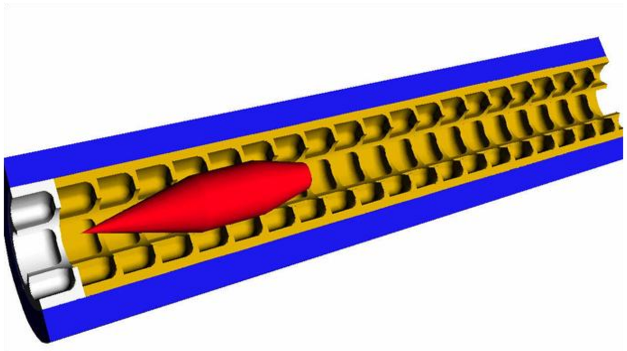

Figure 1. Baffled-tube ram accelerator tube with axisymmetric projectile.

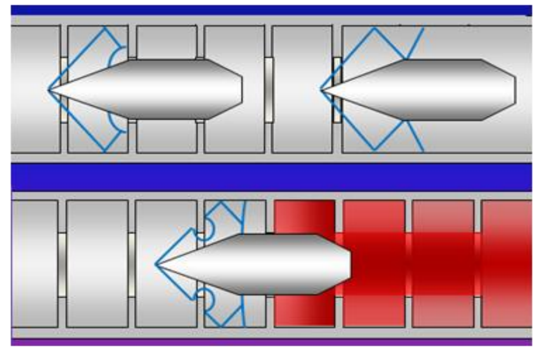

Figure 2. Projectile overtakes shock wave as it expands into baffle chamber.

The BTRA concept utilizes a series of baffles inside a straight bore tube that create a sequential series of chambers, as shown in Fig. 1. [3-5] In this configuration, rails are used to guide the projectile and stiffen the washer-like baffles, forming a sequence of chambers. The baffle spacing is such that the projectile always completely blocks at least one baffle as it passes through the tube. This requires the straight shoulder section to have a length that spans at least one chamber width and one baffle thickness.

The flow field of the BTRA shown in Fig. 2 illustrates how the projectile ingests a fresh charge of propellant as it enters a chamber and compresses the propellant until the projectile shoulder reaches the next baffle. Thereafter the propellant ignition in the combustion zone behind the projectile builds up pressure on its base. In this manner, the BTRA allows the projectile to act as a one-way valve that enables propellant to pass around the projectile yet keeps the combustion-driven shock waves from surging ahead of it. This operating characteristic allows the use of propellants with minimal dilution, which, in principle, could increase thrust by a factor of two or more when using the same fill pressure as an SBRA.

2 Experimental Apparatus and Preliminary Results

Operating characteristics of the BTRA are being investigated with a 2-m-long test section fabricated with removable inserts (Fig. 3-upper left) that slip into a shell tube having instrument stations evenly spaced throughout its length, as shown in Fig. 3-bottom. The shell tube has a 75 mm-I.D. and the 38-mm-bore baffle insert design (Fig. 3-upper right) has 28 chambers per meter (56 chambers for 2-m-long tube). Each baffle chamber has four tapered rails with a 20° wedge angle (tapering from an O.D. arc length of ~16 mm to an I.D. arc length of 2.5 mm) that are staggered at 45˚ between adjacent chambers to enhance structural rigidity. This apparatus design has operational flexibility in that replacement of baffle inserts enables the testing of design variations as desired. Twin end caps, threaded onto the shell tube, compress the inserts to hold them in place. The BTRA test apparatus replaced one of the existing 2-m-long ram accelerator tubes and is instrumented with piezoelectric pressure transducers (PCB 119) and electromagnetic (EM) coil sensors of in-house design.

Experiments have demonstrated accelerations in the range of 50 to 110 km/s^2 with projectiles having a mass of 140 g in $2CH_4$+$4N_2O$ propellant at fill pressures of 1.0 to 2.0 MPa. This propellant has approximately twice the heat release per unit mass than can be used in the SBRA. Shown in Fig. 4 are representative tube-wall pressure data from a 1.5 MPa experiment and the corresponding velocity-distance data. In this particular experiment, the average acceleration was ~70 km/s^2 at an average Mach ~3.85. The EM sensors in the BTRA apparatus were ~35 mm from the circular disc neodymium magnet (10-mm-

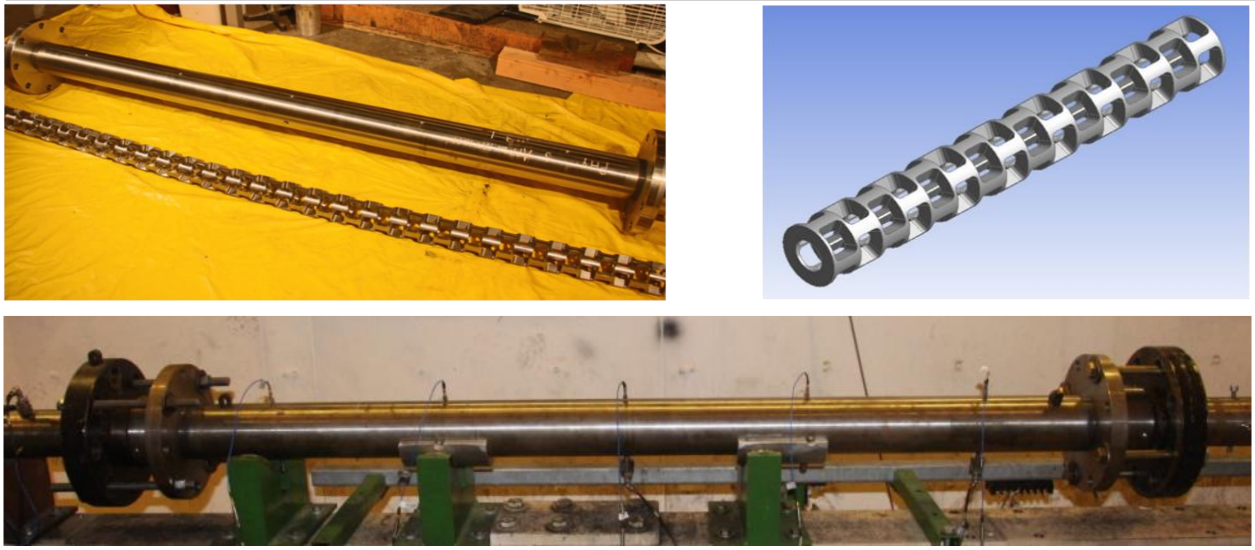

Figure 3. (upper left) BTRA shell tube with 56 baffle chambers; (upper right) isometric view of baffle insert; (bottom) 2-m-long BTRA installed in ram accelerator test section.

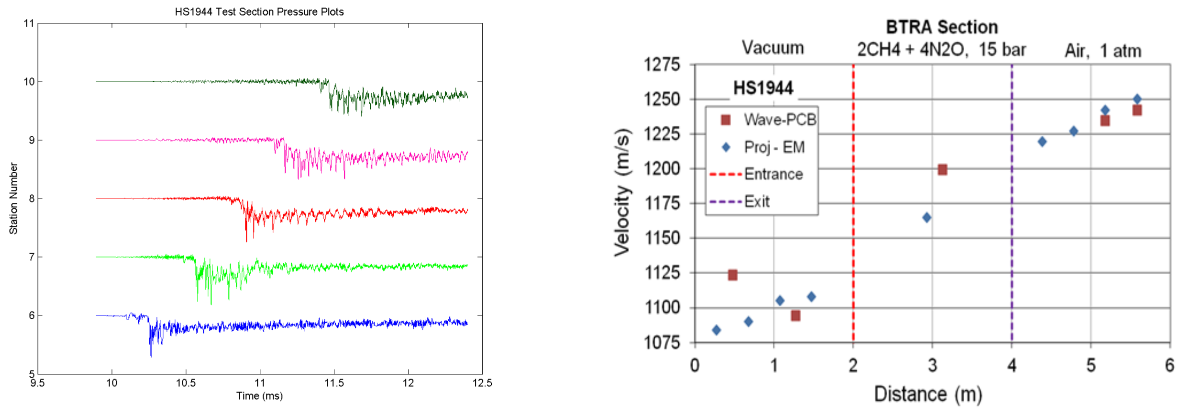

Figure 4. Left: Tube wall pressure data; right: velocity data from BTRA with projectile mass = 140 g, propellant = $2CH_4$ + $4N_2O$, and fill pressure = 15 bar.

O.D. × 2-mm-thick) carried aboard this projectile, which was too great of separation distance for accurate arrival time measurements. Furthermore, the shock waves reflecting within the baffle chambers resulted in tube-wall pressure data that complicated the determination of the projectile arrival time, [6] thus there were no details of the velocity history within BTRA section for this experiment.

The non-dimensional thrust data from BTRA experiments in both CH_4-N_2O and CH_4-O_2-CO_2 propellants are shown in Fig. 5 along with the theoretical non-dimensional thrust curves for a SBRA using $1CH_4$+$2O_2$+$2CO_2$ and $2CH_4$+$4N_2O$ propellants. Note, the definition of the non-dimensional thrust for a BTRA and how it is related to that of a SBRA is

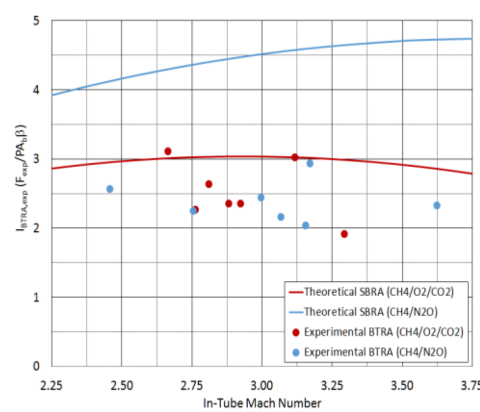

Figure 5. Experimental non-dimensional thrust vs. in-tube Mach number.

presented in [2]. The theoretical Mach numbers for peak thrust were 2.94 and 3.86 for the CH_4-O_2-CO_2 and CH_4-N_2O propellants, respectively. Experiments in CH_4-N_2O propellant (Q ~ 13) carried out at Mach numbers less than that for maximum theoretical thrust had an average ratio of experimental-to-theoretical non-dimensional thrust of ~0.5. Experiments in CH_4-O_2-CO_2 propellant (Q ~ 12) carried out near the peak thrust Mach number had an average experimental-to-theoretical non-dimensional thrust ratio of ~0.85. Thus, it appears that the BTRA can operate quite close to theory in the CH_4-O_2-CO_2 propellant at near the peak thrust Mach number.

3 CFD Results and New BTRA Design

Recent transient CFD simulations using FLUENT have found that the thrust increases significantly by properly orienting the inclination of the baffles. [6] Shown in Fig. 6 are the temperature contours of three different BTRA configurations at Mach = 4 with fill pressure of 5 bar in a $1CH_4$ + $2O_2$ (mole ratio) propellant. The baffles had inclinations of 45° forward, 45° rearward, and zero (i.e., normal to tube wall) in Cases 1, 2, and 3, respectively. The combustion intensity in the projectile vicinity is higher with the rearward inclined and normal baffle orientations (Cases 2 and 3). This correlates with the increased thrust shown in Fig. 7. The periodic thrust solutions, after the transients arising from projectile entrance have stabilized, indicate that the rearward inclined baffle orientation has the highest average thrust.

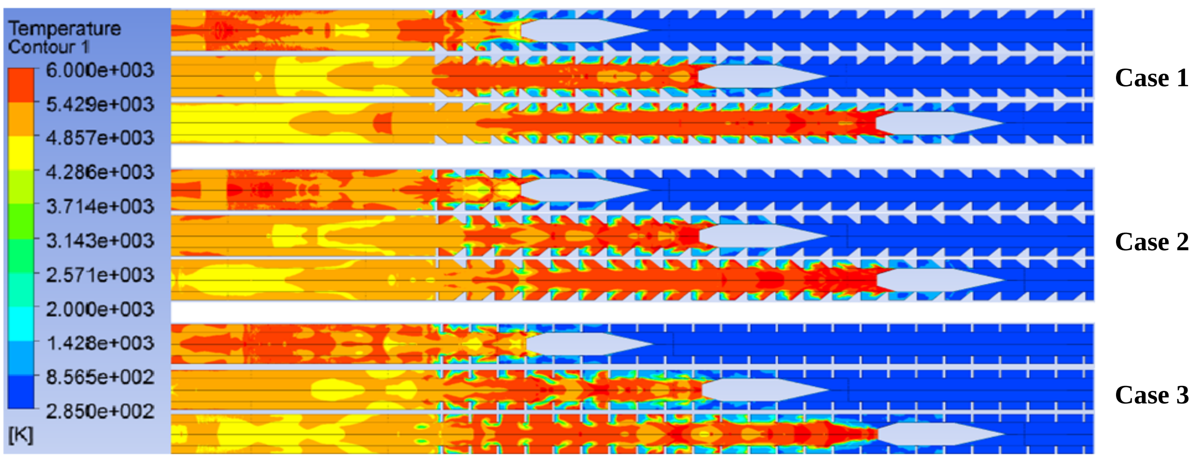

Figure 6. Static temperature contours at 3 projectile positions for Cases 1-3 at M = 4.

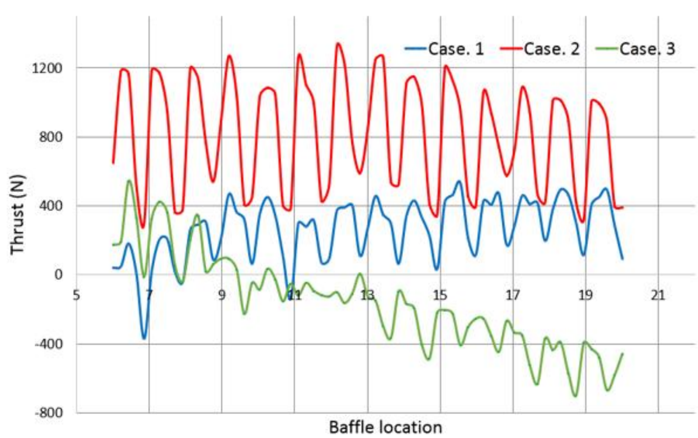

Figure 7. Thrust profiles of Cases 1-3 at M = 4 after BTRA most of the entrance transients have died out.

Static temperature contours of the flow field with the projectile at several different positions in the BTRA are shown in Fig. 8 for Case 2 (Fig. 6), and Cases 4 and 5 in which the ramp angle of the baffles was decreased to 23° and the projectile tail cone length was varied by changing its

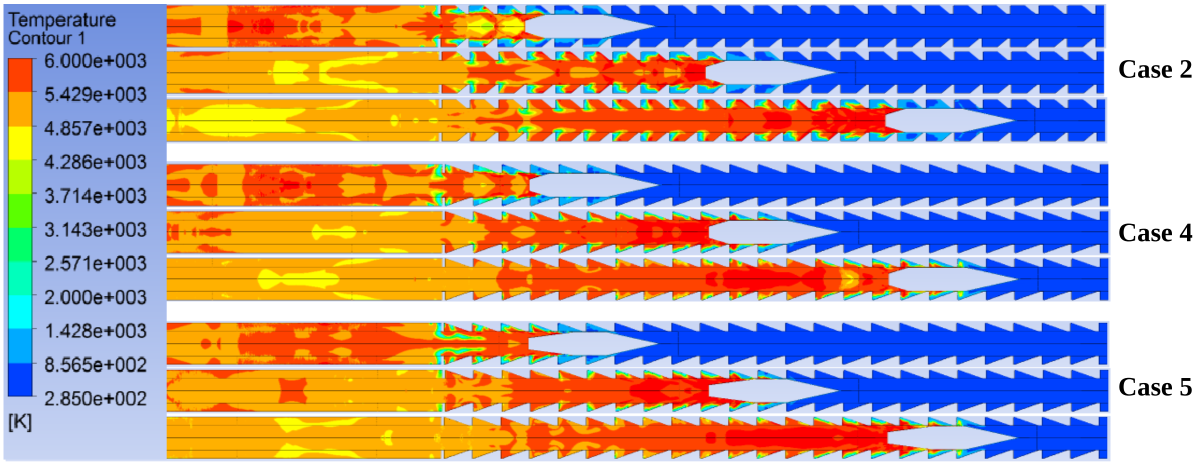

Figure 8. Static temperature contours at 3 projectile positions for Cases 2, 4, and 5 at $M = 4$.

divergence angle from 20° to 9°. The temperature contours indicate that the more inclined baffles promote the combustion to reach completion in fewer baffles, and that the combustion moves farther up onto the projectile when the tail cone is lengthened as was done for Case 5.

The impact on thrust generation of these baffle and projectile variations is shown in Fig. 9. Both Cases 4 and 5 had average thrusts about 3 times greater than that of Case 2, although the difference in projectile geometry seemed to have little effect. A transient thrust peak was observed for Case 4 around the 16th baffle; however, this is likely a numerical artifact that can be eliminated by extending the computational domain (more baffles) until the periodic solution is obtained. In any case, it is conclusive that rearward-slanted projectiles improve BTRA thrust performance and more shallow ramp angles are preferred. Optimization studies have not yet been attempted.

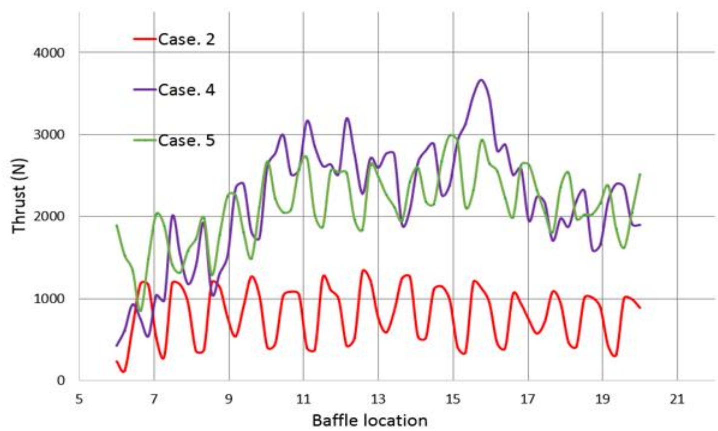

Figure 9. Thrust profiles of Cases 2, 4 and 5 at $M = 4$ from baffles numbered 6 to 20 from the entrance.

The results presented here along with others from this particular CFD investigation have led to the design and fabrication of a new set of baffles with a rearward (toward breech) ramped orientation. This BTRA configuration not only incorporates this first step toward geometry optimization, it also allows for operation at fill pressures of up to 50 bar. The assembly of this new system is currently in progress and testing will commence shortly. The results from this phase of the research program will be key in determining if the BTRA technology can fulfill its promise of generating more thrust than the conventional smooth bore ram accelerator at lower fill pressures.

4 Conclusions

Experiments have shown that propellants with very high heat release (minimal diluent) generate thrust in the BTRA in the Mach range of 2.2 to 4. The experimental thrust, however, is about 15 to 50% less than predicted. Transient CFD modeling has shown that baffles inclined toward the projectile, resulting in a converging flow area profile as the projectile moves through the baffle chamber, produce substantially more thrust than baffles that are normal to the tube wall or inclined away from the projectile. New experiments are in progress to validate the predicted effects of inclined baffles and examine BTRA operation at fill pressures up to 50 bar.

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