Ram Accelerator Operation at 15 to 20 MPa Fill Pressure

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Summary

An investigation of the experimental conditions which permit ram accelerator operation at fill pressures up to 20 MPa, the highest operating pressure achieved to date, is reported. Titanium alloy projectiles at entrance velocities as low as 1200 m/s were successfully started in propellants at fill pressures of 15-20 MPa, and continuous acceleration was achieved in one- and two-stage experiments in a 4-m-long test section. A peak velocity of ~2100 m/s and average thermally choked ram accelerator acceleration of ~46,000 g were attained with 118 gm projectiles in 20 MPa propellant. Due to real gas effects on the acoustic speed of the propellant, the throat-to-bore diameter ratio of the projectiles needed to be reduced from the nominal value of 0.76 to 0.60 in order to enable operation at pressures greater than 15 MPa. The average accelerations achieved in these experiments were lower than those predicted by the real-gas one-dimensional quasi-steady control volume model; however, ongoing theoretical analyses indicate several factors that may account for the discrepancies between theory and experiment.

Introduction

The ram accelerator is a hypervelocity launcher that uses a ramjet-like propulsive cycle to generate thrust for projectiles. The thrust is proportional to the fill pressure and increases with increasing heat release from propellant combustion.[1] The highest possible performance for a given projectile mass will thus be obtained by using the maximum fill pressure the facility can accommodate, and with the most energetic propellant that will sustain ram acceleration. The primary focus of the high pressure ram accelerator research is to address the logistical challenges presented by the extreme aerothermal environment to which the projectiles are subjected under conditions of high pressure operation.

The thermally choked ram accelerator propulsive mode[2] is initiated by launching a subcaliber projectile into a tube containing a premixed gaseous propellant and establishing the self-sustaining combusting flow field, as shown in Fig. 1. This propulsive mode is characterized by subsonic combustion and a projectile velocity less than the Chapman-Jouguet detonation speed of the propellant. During the starting process, the occlusion provided by a full-bore obturator drives a normal shock wave onto the rear body of the projectile. Propellant ignition occurs as a result of the complex interactions of shock waves in the residual air in the launch tube (resulting from imperfect evacuation) with the projectile, obturator, and diaphragm at the entrance to the test section.[3] The ram accelerator is successfully started once supersonic flow is established behind the projectile throat (the cross-section of minimum flow area) and the normal shock wave produced by the obturator is stabilized on the rear body of the projectile by thermal choking of the reacting flow behind the projectile.

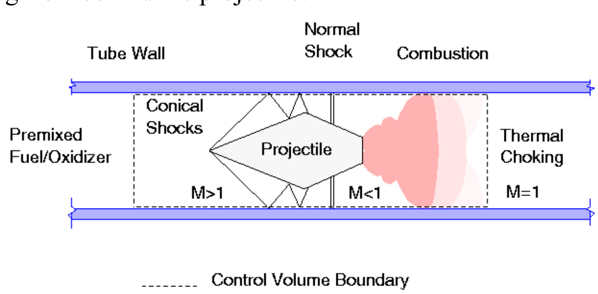

Fig. 1. Thermally choked ram accelerator propulsive mode.

If supersonic flow is not established behind the throat due to factors such as insufficient entrance velocity, nose cone damage, or substantial heat release ahead of the throat, the flow chokes at the throat and the normal shock wave is driven ahead of the projectile. This result is referred to as a "sonic diffuser unstart" (SDU). If the normal shock wave overtakes the throat at some time after supersonic flow is established behind the throat, the resulting failure is referred to as a "wave unstart". A wave unstart can be caused by excessive heat release from the propellant, excessive obturator mass, or other factors. In either case, thrust ceases and the projectile decelerates.

Experimental Facility

The 38 mm facility at the University of Washington enables ram accelerator experimentation at propellant fill pressures of up to 20 MPa. The first 4 m of the ram accelerator test section, shown in Fig. 2, consists of two 1-m-long and one 2-m-long high pressure tubes, with a bore diameter of 38 mm and an outer diameter of 152 mm.[4] The high pressure tubes are manufactured from AISI 4340 steel and are designed for a maximum static load of 1000 MPa. The remaining 12 m of the test section is comprised of six low pressure tubes manufactured from AISI 4140 steel, each 2 m in length, with outer diameters of 102 mm, and are designed to withstand a static load of up to 550 MPa.[5]

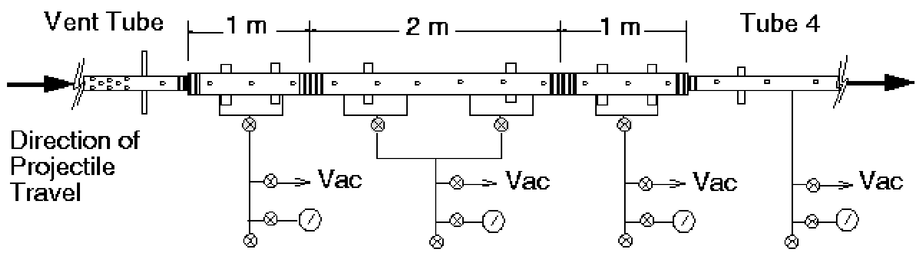

Fig. 2. High pressure test section schematic.

Each 1-m-long tube (Fig. 2) has three instrument stations with diametrically opposed ports; the 2-m-long tube has six pairs of ports. These stations are spaced along the tubes at 333 mm intervals. The first instrument station in the high pressure section is 167 mm from the entrance diaphragm. The last station in the high pressure tubes is spaced 167 mm from the exit and 396 mm from the first instrument port in the low pressure part of the test section. The instrument ports can accommodate electromagnetic (EM) probes and PCB model A119A11 or A119A12 piezoelectric pressure transducers (550 or 800 MPa maximum pressure range, respectively).[5]

All of the tubes in the high pressure test section have two fill ports isolated from the fill lines by air-actuated Snotrik valves (300 MPa rated), which separate the gas handling system from the extreme pressure pulses generated in the experiments. The low pressure part of the test section has a fill port in each 2 m tube section. Mylar diaphragms can be inserted between any pair of adjacent tubes, enabling multiple stages of different propellants, and hence acoustic speeds, to be used. Any tubes not filled with a propellant are evacuated. Details of the light gas gun pre-launcher, propellant filling system, and other major system components can be found in Refs. 4, 6, and 7.

Several different projectile geometries were used in this investigation. Four-finned one-piece projectiles were manufactured from titanium 6Al-6V-2Sn alloy in a single basic design, with adjustments to the geometry machined post-fabrication, as necessary for individual experiments. The basic design is shown in Fig. 3a, with body length determined as required for each particular experiment. The projectiles feature fin spans of 38 mm, throat diameters of 23 mm, nose cone angles of 12.5°, and fin rake angles of 20°. The interior of the projectile body is hollow to minimize the projectile's overall mass. A neodymium magnet is inserted and held at the projectile throat by a threaded magnesium plug. The fin leading edges are knife-edged at 15° in order to reduce the strength of the attached shock waves near the projectile throat. The total masses of the projectiles ranged from 106 to 135 gm, depending on their characteristic design parameters.

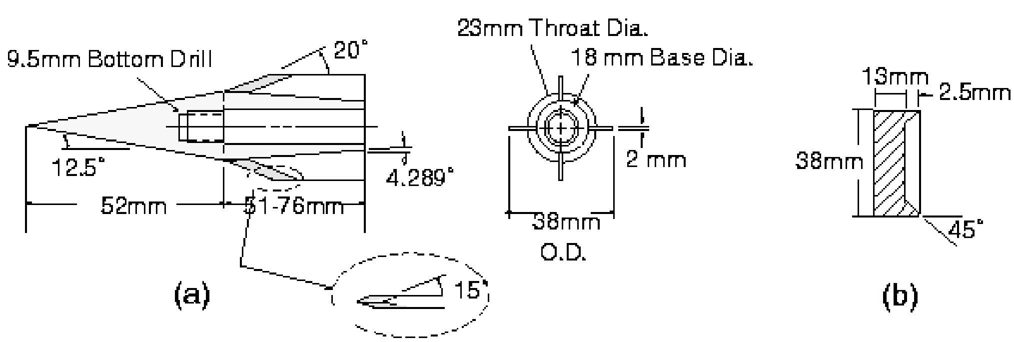

Fig. 3. a) Generalized Ti alloy projectile design. b) Obturator design.

The obturator, shown in Fig. 3b, is placed behind the projectile base to prevent gas blow-by from the light gas gun pre-launcher and to drive a normal shock onto the projectile rear body upon entrance to the test section, as required by the starting process.[8] The obturator is manufactured from polycarbonate and has a mass of approximately 18 gm. It is glued to the projectile with cyanoacrylate adhesive for the process of loading the two into the light gas gun.

Results and Discussion

The dimension of the projectile throat is a critical parameter in high pressure ram accelerator experiments. In order to effect a successful start, supersonic flow must be achieved behind the projectile throat. The minimum Mach number required to fulfill this condition is that which causes the supersonic flow to become choked at the projectile throat (SDU). While a steady ideal gas flow model has been useful in determining the minimum required SDU velocity when the fill pressure is 5 MPa or less, experiments conducted at 7.5 MPa indicated that the minimum |SDU velocity is greater than the model predicts.[6,9]

At fill pressures greater than 5 MPa, it becomes necessary to use a real gas equation of state to accurately model ram accelerator performance.[5,6,9,10] When real gas effects are accounted for by a non-ideal equation of state, the acoustic speed of the propellant varies with fill pressure, and thus affects the minimum Mach number required for starting the ram accelerator. The variation of acoustic speed with fill pressure for a typical propellant modeled with the Redlich-Kwong equation of state is shown in Fig. 4.[5] The ideal gas acoustic speed is shown in the figure for comparison.

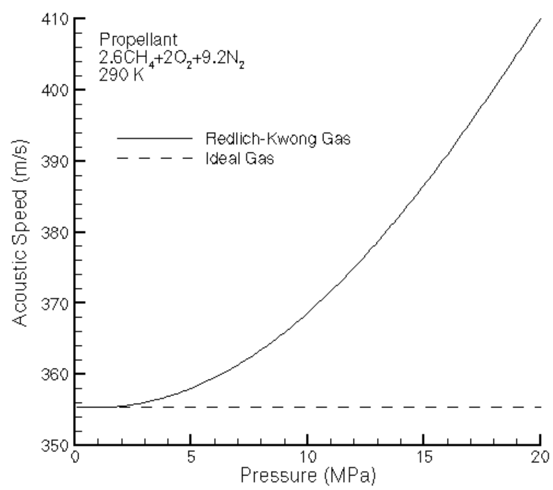

Fig. 4. Variation of $2.6CH_4+2O_2+9.2N_2$ acoustic speed with pressure at 290 K.

The model accounts for both the enthalpy deviation from non-ideal gas behavior and the variation of the specific heat capacity with pressure and temperature.[11] Since the acoustic speed of the quiescent propellant increases with fill pressure, the projectile is required to have a higher entrance velocity to avoid flow choking at the projectile throat and thus a start failure. To reduce the entrance velocity requirement, the projectile throat diameter must be reduced, thus decreasing the Mach number necessary for successful starting. Previous experiments at high pressure have demonstrated that reducing the throat-to-bore diameter ratio from 0.760 to 0.667 was necessary to enable starting at fill pressures greater than 11 MPa with entrance velocities of ~1200 m/s, while at fill pressures greater than 15 MPa, a further reduction to 0.600 was needed.[5,6]

Data collected from earlier experiments[5] using only the first 1-m tube suggested a projectile design that would successfully start at 15 MPa. The projectile geometry used in the experiment described here is as shown in Fig. 3a, with a 76 mm aft body, 18 mm base diameter, and a mass of 118 gm. The test section for the experiment was a 4-m stage of $2.6CH_4+2O_2+9.2N_2$ propellant at 15 MPa. The velocity-distance data from this experiment are shown in Fig. 5, along with the theoretical performance predicted for these conditions by the one-dimensional control volume method[12] using the Boltzmann equation of state. The use of a real gas equation of state helps to account for the pressure-dependent variation of the heat release derived from combustion of the propellant and the acoustic speed of the gas at the thermally choked state,[6] which affect the expected thrust performance.

The experimental data indicate the projectile experienced very weak thrust over the first meter of the stage. If the theoretical data are considered starting from the beginning of the second meter (translated to the right as shown in Fig. 5), the velocity-distance profiles are in better agreement. This weak acceleration during the starting process has been observed in other ram accelerator facilities at pressures as low as 3 to 4.5 MPa.[13] The late development of the thermally choked velocity profile may be caused by highly unsteady flow effects, rapid deceleration of the obturator, the induction time of the propellant at high pressure, or a combination of these and other causes; the subject is under investigation. The average acceleration over the final 3m was 31,400 g.

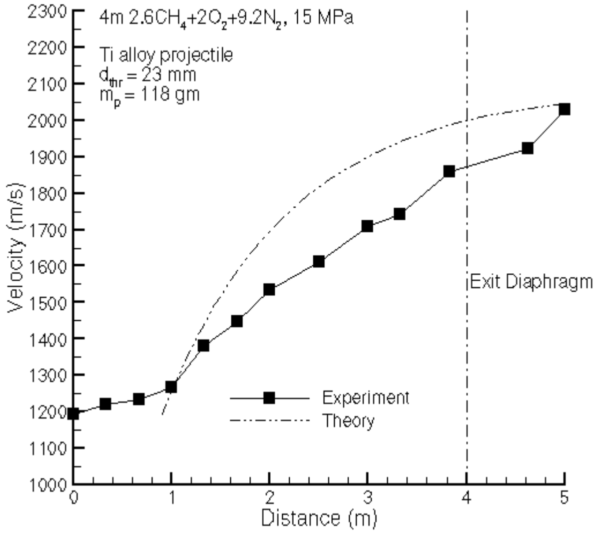

Fig. 5. Results from 4-m 15 MPa experiment.

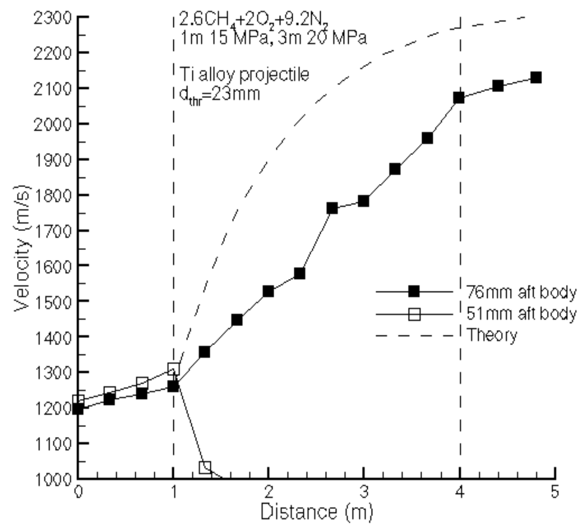

Fig. 6. Results from two-stage 15/20 MPa experiments.

Additional experiments were conducted using Ti projectiles in test sections consisting of a 1-m stage at 15 MPa followed by a 3-m stage at 20 MPa. Both stages used $2.6CH_4+2O_2+9.2N_2$ as the propellant. The projectile aft body ranged in length from 51 to 76 mm; the projectile masses varied from 105 to 118 gm. The velocity-distance data from these experiments are shown in Fig. 6, along with theoretical data for the conditions of the 76 mm body experiment in the 20 MPa stage.

The 76 mm aft body projectile starts and continuously accelerates throughout the test section, for an average 46,000 g acceleration in the 20 MPa stage, while the 51mm aft body unstarts early in the second stage. Wall pressure data from these experiments indicate that in the case of the 51 mm aft body, the projectile was severely canted just before the wave unstart occurred. The severe aerothermal environment produced by the thermally choked ram accelerator flow field at these pressures may be such that the projectile fins are degraded to a degree that makes the projectile unstable; projectiles recovered after these experiments corroborate this hypothesis.

An additional experiment was conducted using a Ti projectile in a 4-m test section, with $2.6CH_4+2O_2+9.2N_2$ at 20 MPa as the propellant. The projectile aft body was 64 mm in length; the overall mass of the projectile was 106 gm. The projectile was launched into the test section at 1250 m/s and successfully started and continuously accelerated throughout the length of the test section. The velocity-distance data and the corresponding theory, translated to the right to compare predicted performance outside of the region influenced by the starting process that occurs in the first meter of the test section, are shown in Fig. 7. The agreement between the theoretical and experimental results is similar to that achieved in the 4-m 15 MPa experiment (Fig. 5), though the discrepancy between the two is slightly greater in the 20 MPa case; the average acceleration over the last 3 m was 38,600 g. This may be partially attributed to unsteady flow effects unaccounted for by the theoretical model, which become greater in magnitude as the fill pressure of the stage increases.

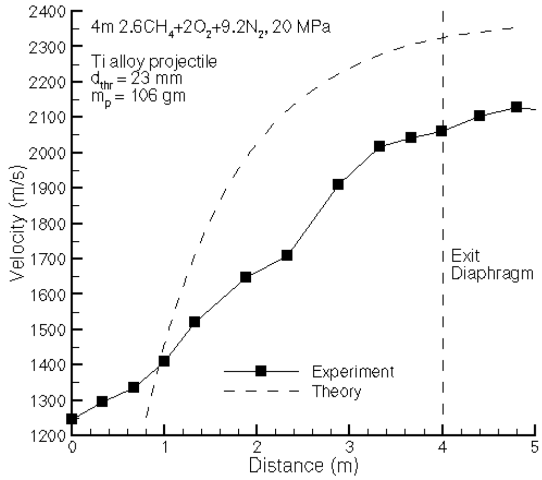

Fig. 7. Results from 4-m 20 MPa experiment.

Conclusions

Experiments in the 38 mm bore ram accelerator have demonstrated starting of projectiles with throat-to-bore diameter ratios of 0.600 in 15 and 20 MPa propellants and continuous acceleration in stages at 15 and 20 MPa. The decrease in throat diameter from previous projectile designs is necessary in part due to the increased acoustic speed of the propellant at high fill pressures. The projectiles experience a period of relatively weak acceleration over the first meter of test section before nominal ram accelerator operation is achieved. Average accelerations of 31,400 and 46,000 g were observed over the last 3 m of the test section using 118 gm projectiles in propellants at 15 and 20 MPa fill pressures, respectively. Ram accelerator operation at velocities up to 2070 m/s was demonstrated in 20 MPa propellant.

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