New Tools for Ram Accelerator Performance Modeling

Sebastien Depraz[1,2], Carl Knowlen[2], Pascal Bauer[1], Andrew J. Higgins[3]

[1]Laboratoire de Combustion et de Détonique, UPR 9028 CNRS,
ENSMA, BP 40109, 86961 Futuroscope, France

[2]Department of Aeronautics and Astronautics, University of Washington,
Box 352250, Seattle, WA, 98195, USA

[3]Department of Mechanical Engineering, McGill University, 817 Sherbrooke St. W.,
Montreal, Quebec H3A 2K6, Canada

1 Introduction

Detailed modeling of the quasi-one-dimensional flow properties of a ram accelerator operating in both the subdetonative and superdetonative velocity regimes is being carried out. The impact on projectile acceleration due to shock waves, chemical reactions, friction, and other phenomena is being determined using a modified version of the NASA Chemical Equilibrium with Applications program. Comparisons with tube wall pressure data and velocity-time data from ram accelerator experiments at Mach numbers ranging from 3 to 6.5 are used to determine the validity of the detailed flow models. In particular, new data under conditions in which the projectile was cruising at nearly constant velocity at hypersonic Mach numbers are modeled in detail.

2 Theoretical Modeling

Previous work has shown that detailed flow field information is not always necessary to determine the effects of propellant heat release on thrust performance over a wide range of ram accelerator operating conditions. Nevertheless, the pressure and temperature properties of the flow around the projectile are of interest when considering various propulsive cycle operating characteristics. Computational fluid dynamic studies are useful for these purposes; however, they do not readily lend themselves to parameterization applications involving a wide range of propellants and projectile geometries. Thus a steady, quasi-one-dimensional flow field model has being developed which accounts for area change, pressure drop, and chemical energy release on a station by station basis. The influence of skin friction and form drag are accounted for in the net thrust calculations.

This propulsive cycle analysis is conducted in the projectile frame of reference using the control volume shown in Fig. 1. The ideal gas equation of state is used and the flow is considered adiabatic. The standard channel flow equations are applied to determine flow properties at each station. Ram compression over a conical nose cone occurs between the entrance to the control volume (station1) and the point of maximum flow contraction (station2), which corresponds to the projectile "throat." The total pressure drop associated with conical shocks on the nose cone and the shock losses generated by the fins are accounted for in the flow at station 2. The

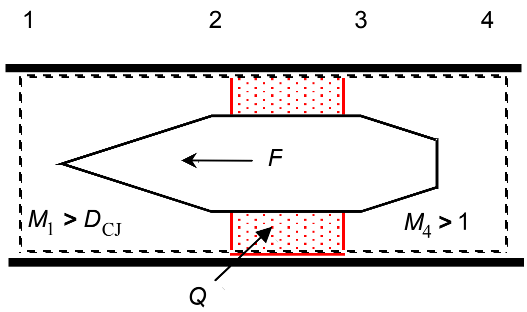

Fig. 1 Ram accelerator control volume

chemical heat release is assumed to occur supersonically at the projectile throat, between stations 2 and 3, with the combustion products determined from a computer code which computes the chemical equilibria based on constant mass flux and the flow properties at station 2. The expansion process between stations 3 and 4 incorporates expansion losses to accommodate the bluff base of the projectile. Skin friction drag is also included for the net thrust prediction at any flight Mach number. Details of the theoretical modeling will be presented.

3 Experimental Results

An experimental investigation of the superdetonative ram accelerator under low acceleration operating conditions was conducted in the 38-mm-bore ram accelerator facility at the University of Washington. Titanium-alloy projectiles were launched into reactive propellants at Mach numbers greater than 5.5 to determine if the combustion process could be shock initiated and stabilized, what levels of thrust can be generated, and to evaluate the reactivity of the projectile material in hypersonic flow. The results of these experiments using methane- and ethane-based propellants are used to facilitate the development of the flow field model. Pertinent results from these experiments are presented below.

The thrust performance of the ram accelerator under hypersonic operating conditions is sensitive to both the propellant composition and the projectile geometry. A series of experiments was conducted in which the carbon dioxide molar level in a $1.5CH_4+2O_2+XCO_2$ propellant was varied in the range $2.8 < X < 8$. The velocity-distance data from these experiments are shown in Fig. 2-left. The projectiles entered the third stage test propellant in the velocity range of 1.87 – 1.93 km/s, corresponding to a Mach range of 6.0 – 6.3. The largest velocity increase (160 m/s) and peak velocity (2.07 km/s) were observed in the $5CO_2$ (HS1679) propellant. More energetic propellants (2.8 and $4.1CO_2$) experienced unstart within 2 m or less after entering the third stage. The greatest distance (~5 m) of projectile acceleration occurred in the propellant with $7CO_2$ (HS1673), where it reached ~1.98 km/s before unstart. In two firings into $6CO_2$ propellant (HS1682, HS1685), the projectile accelerated for more than 3 m and attained 1.96 km/s before unstart, demonstrating very reproducible results. At a dilution level of $8CO_2$, the projectile more or less just cruised at ~1.91 km/s ($M = 6.6$) for ~3 m before unstart. It is not known whether this unstart was due to projectile erosion/failure, combusting boundary layer interactions arising from surface heating of the projectile, and/or other gas dynamic phenomena.

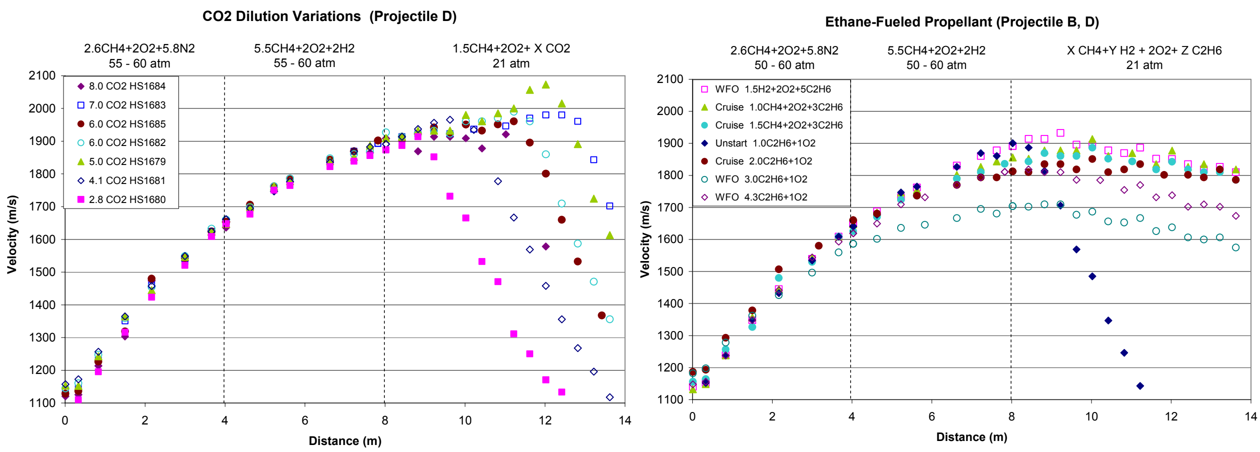

Fig. 2 Velocity data from ram accelerator experiments in methane- and ethane-fueled propellants.

Experiments were also carried out at hypersonic Mach number in ethane-fuel based propellants. In some cases, the combustion waves clearly fell off projectiles and they smoothly decelerated at supersonic velocity (from about Mach 5.5 down to 5.1) in the last four meters of the test section. Experiments with this behavior are labeled as WFO in the plot legend (Fig. 2-right). When the ethane content was adjusted to formulate $2C_2H_6+1O_2$ propellant ($V_{CJ} = 1.80$ km/s), the combustion wave did not completely separate in the first 3 or so meters of the test section. Enough thrust was generated to offset the drag and allowing the projectile to “cruise” at relatively constant velocity. Eventually, the combustion wave clearly fell off the projectile in the last two meters of the test section and the projectile velocity decreased to the CJ speed of the propellant. It is unusual for a projectile to experience a wave fall off when traveling at velocities greater than the CJ speed of the propellant, as evident is the CO_2-diluted series of experiments. In the last of the pure ethane-oxygen experiments (HS1677), the projectile was injected into $1C_2H_6+1O_2$ (V_{CJ} = 2.24 km/s) with an entrance velocity of 1.9 km/s (Mach 6.1, $V = 0.85 V_{CJ}$). In this scenario the projectile promptly unstarted, which is to be expected when trying to operate in the thermally choked velocity regime with too energetic propellant.

The tube wall pressure-time data from a representative experiment in which a projectile was launched at a velocity of ~1.9 km/s (Mach number ~6.5) into $1.5CH_4+2O_2+6CO_2$ propellant are shown in Fig. 3. These data are time-synchronized with respect to the passage of the neodymium magnet carried on board the projectile. Pressure amplitude scale is in 1 volt intervals, corresponding to pressure values of ~70 MPa. Individual pressure sensor calibrations have yet to be applied to the data presented here. The nominal operating conditions for this situation are reflected by the pressure data portrayed in the first four pressure traces (starting from the bottom of Fig. 3). Both the pressure on the aftbody of the projectile and the strength of the reflection of the lead conical shock increases with increasing Mach number. The upper two pressure traces show a strong shock wave moving out in front of the projectile, characterizing an unstart. The projectile abruptly decelerates after unstart and experiences extensive aerodynamic heating as it pushes an over-driven detonation wave ahead of it. Many pressure records of these phenomena have been collected and are currently being processed.

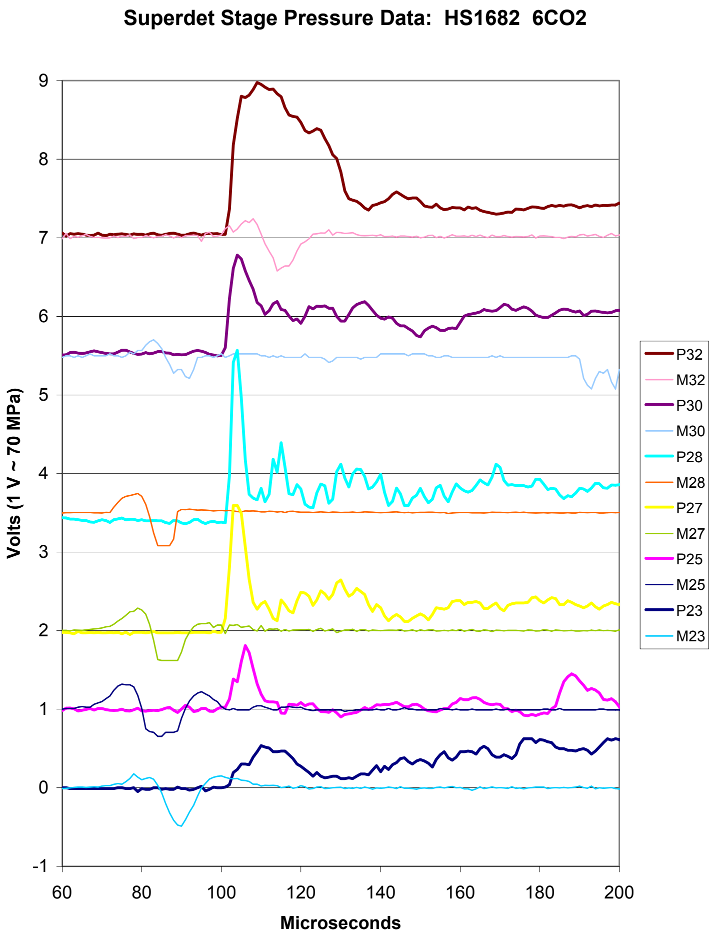

Fig. 3 Pressure data from hypersonic ram accelerator experiment.

4 Summary

Detailed modeling of the flow field is being used to gain a better understanding of both the thrust characteristics and detailed flow field phenomena observed in ram accelerator experiments. It is crucial to understand the nature of the unstart process observed in this particular experimental series to determine if the limiting phenomena are mainly gas dynamic in nature or if projectile material limitations are being reached. Results of this modeling effort will be presented.