Experimental Investigation of Shock-Induced Combustion Propulsion

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1 Introduction

The shock-induced combustion ramjet (or "shcramjet") potentially offers advantages over the conventional diffusive-combustion scramjet. In particular, fuel injection on the vehicle forebody results in an effectively premixed mixture of fuel and air entering the combustor. This feature permits either shock-induced or detonative modes of combustion to be utilized in the combustor, which are much more rapid than the usual diffusion-controlled combustion of the conventional scramjet. Thus, the "shcramjet" may address one of the major problems of the conventional scramjet; i.e., unacceptably long combustor lengths (with corresponding unacceptably large drag losses). [1]

An experimental investigation of the shock-induced combustion propulsive cycle was conducted in the 38-mm-bore ram accelerator facility at the University of Washington. Titanium-alloy shock-induced combustion projectiles were launched into premixed 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 experiments using methane- and ethane-based propellants with and without carbon dioxide diluent are summarized.

2 Experimental Apparatus and Procedures

The 38-mm-bore ram accelerator test section was configured to initially accelerate projectiles with the thermally choked ram accelerator propulsive mode from an entrance velocity of ~1.1 km/s up to ~1.8 km/s through two propellant stages, each 4-m-long. Details of this experimental procedure can be found in Knowlen et al. [2] These stages, filled with $CH_4/O_2/N_2$ and $CH_4/O_2/H_2$ propellants to 50-60 bar, were necessary to augment the gas gun muzzle velocity to the point where shock-induced combustion tests could be carried out at Mach ≈ 6 in CO_2-diluted propellant. Acceleration in these two stages proved to be very reliable and incurred minimal projectile erosion at Mach numbers less than 4.5. Hypersonic experiments were then conducted in a 6-m-long third stage of the ram accelerator test section with various CH_4- and C_2H_6-fueled propellants at 21 bar fill pressure.

The entrance velocity to the third stage test section containing the low sound speed propellant ranged from 1.7–1.9 km/s for these shock-induced combustion experiments. Tube-wall pressure was monitored at 80-cm-intervals throughout most of the third stage part of the test section, whereas the electromagnetic probes in this stage were separated by 40 cm. Projectile velocity was based on center-differencing of time-of-arrive data from the EM probe signals, and the velocity of the lead pressure wave was determined from pressure transducer data. Two different classes of propellant were used: (i) a $1.5CH_4+2O_2$ propellant diluted with variable amounts of CO_2 and (ii) a $C_2H_6+3.5O_2$+diluent propellant, where excess C_2H_6 and sometimes CH_4 or H_2 were added as diluents.

The projectile configuration most extensively tested during this research program was fabricated as one piece from titanium 6Al-4V alloy. It was hollowed from the base primarily for mass reduction purposes and to accommodate the installation of a neodymium magnet. Features to enhance operation at hypersonic velocity incorporated in this projectile design are a slightly rounded nose tip (0.25 mm radius), knife-edged fins at a 20˚ rake angle and 3.81-mm-thickness, throat diameter of 30.0 mm (0.76 throat-to-tube diameter ratio), and a 71.1-mm-long body with a taper angle of 4.49˚. The hollow base allows pressure equalization to eliminate concerns of projectile collapse from external pressure loads. These projectiles had a mass range of 106 – 118 g, depending on details of the internal and external geometry.

Fig. 1 Experimental projectile.

3 Experimental Results

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 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 Mach-distance and *V/Vcj*-distance data from these experiments are plotted in Fig. 2a and 2b, respectively. 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.

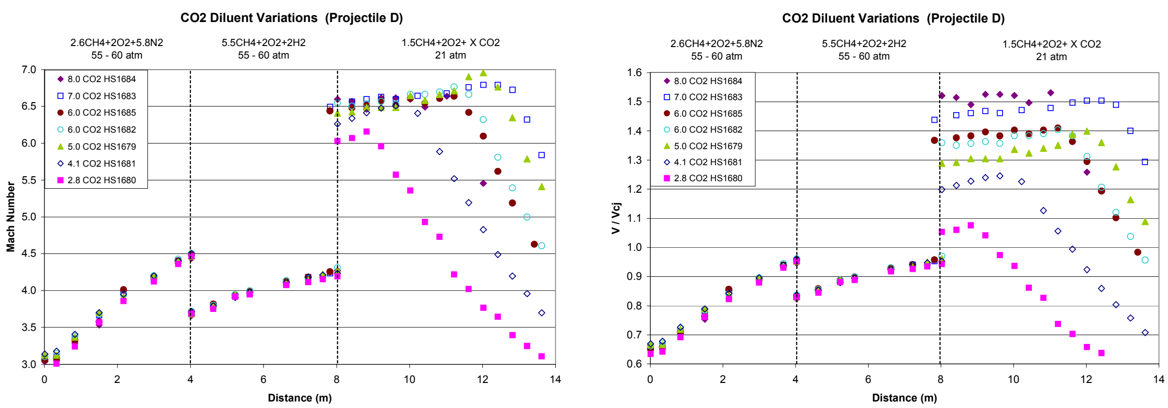

Fig. 2 (a) Mach-distance data and (b) *V/Vcj*-distance data from two thermally choked stages and shock-induced combustion test section having CH_4–fueled propellant.

As evident in Fig. 2a, the projectile Mach number upon entering the third stage of these experiments does not vary much in the range of CO_2 dilution levels investigated here. The CJ speed, however, varied by ~50% ($1.25 < V_{CJ} < 1.78$ km/s). The influence of CJ speed is more apparent when plotted in the format in Fig. 2b; i.e., where the projectile velocity is normalized by CJ speed in the *V/Vcj*-distance plots. The projectile is accelerated up to ~95% CJ speed in the two thermally choked stages and undergoes a sudden transition to superdetonative velocity upon entrance to the third stage. In the most energetic propellant ($2.8CO_2$) the entrance velocity is only 5% greater than CJ speed and the projectile unstarts within ~1 m. The highest average specific thrust (151 N*s/kg with average acceleration = 9100 g) was attained when entering at 20% greater than CJ speed in $4.1CO_2$ diluted propellant; however, as previously stated, this projectile only accelerated ~2 m before unstart.

More stable operation was achieved when the third stage entrance velocity was higher than CJ speed by 30% or more. In these scenarios the projectile readily operated with a shocked-induced combustion propulsive cycle for 3 or more meters before it experienced an unstart.

There was concern that the methane-oxygen equivalence ratio ($\phi = 1.5$) in the CO2-diluted experiments was so close to stoichiometric that some degree of titanium burning may be occurring. Thus experiments were carried out with ethane-rich propellants formulated to have similar heat release per mass, CJ speed, and sound speed as the CH_4-fueled propellant. Since the stoichiometric ratio of ethane-oxygen is $1.0C_2H_6 : 3.5O_2$, propellants having more than 50–50 ratio of C_2H_6 to O_2 are very fuel rich which minimizes the amount of oxygen available for metal combustion. In addition, due to its more complex molecular make up, the heat capacity of C_2H_6 is larger than that of CH_4 and CO_2 on a molar basis which makes it a very good diluent. These characteristics of ethane motivated experimentation with third stage ethane-oxygen propellants formulated to have ~300 m/s sound speed and CJ speeds of 1.5 to 1.7 km/s. Projectile entrance velocities of 1.8 – 1.9 km/s were used in this set of experiments and the resulting Mach-distance and V/V_{CJ}-distance data are shown in Figs. 3a and 3b, respectively.

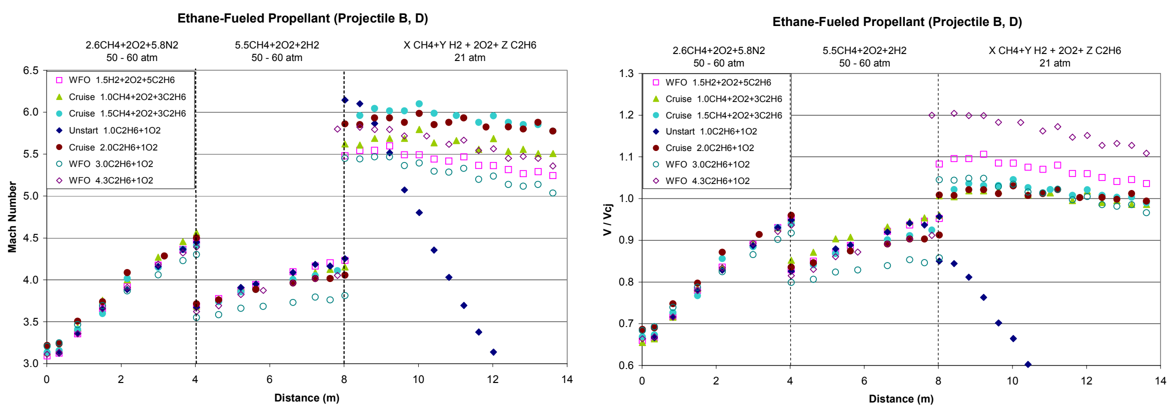

Fig. 3 (a) Mach-distance data and (b) *V/Vcj*-distance data from two thermally choked stages and shock-induced combustion test section having C_2H_6–fueled propellant.

Two test firings were carried out with $4.3C_2H_6$+1O2 and $3.0C_2H_6+1O_2$ propellants having theoretical CJ speeds of 1.50 and 1.62 km/s, respectively. In the $4.3C_2H_6$ experiment the projectile entered the third stage at Mach 5.8, a velocity 20% higher than CJ speed whereas in the $3.0C_2H_6$ experiment the projectile entered the third stage at Mach 5.5, an entrance velocity only 5% higher than CJ speed. Remarkably, the combustion waves clearly fell off both of these 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. Average drag forces (~25 kN) determined from the three WFO experiments shown here correspond to a drag coefficient of 0.09±0.01, based on projected frontal area of the projectile, in the Mach range of 5.3 to 5.7.

When the ethane content was further reduced 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, $V = 0.85V_{CJ}$). 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 of propellant.

4 Discussion

Theoretical predictions of superdetonative ram accelerator operation with $1.5CH_4+2O_2+XCO_2$ propellant at 21 bar and similar projectile configuration indicate that the *thrust = drag* limit should be reached at velocities 40-50% greater than CJ speed. This indeed appears to be velocity ratio limit observed here in experiments using propellant dilution levels of $5 < X < 8$ CO_2 (see Fig. 2b). Ideally the projectile should cruise throughout the remainder of the test section at constant velocity once this gas dynamic limit has been reached, which would correspond to hypersonic cruising conditions in a shock-induced combustion engine application. The relatively small scale at which these experiments were carried out, however, certainly magnifies the impact of aerodynamic and/or combustion heating effects on the projectile. Thus, due to erosion effects, the ability to maintain constant velocity operation for long stretches in the test section may not be possible for titanium alloy projectiles.

Data in Fig. 3b indicate that sustained shock-induced combustion operation at velocities greater than the propellant CJ speed was not demonstrated in any of the experiments with excess ethane present. Indeed, the subsequent wave fall-off behavior was not seen under any circumstances in the $CH_4/O_2/CO_2$ propellant. It is possible that propellant combustion could not be initiated on the aft body of the projectile at the lower Mach number (5.5-6.1 vs. 6-6.6) and fraction of CJ speed ($1.2V_{cj}$ max vs. $1.5V_{cj}$ max) of these experiments. Another possibility is that the tendency for metal combustion was completely suppressed which negatively impacted the ability for a supersonic combustion process to stabilize in a manner that would continuously accelerate the projectile. This kind of metal combustion interaction phenomenon has been suggested by Seiler et al. [3] The observation of a distinct pressure wave falling behind the projectile in the ethane-fuel experiments implies that whatever thrust was seen may not even have been from oblique shock-induced combustion; i.e., carry over effects from the prior thermally choked stage may have had some influence.

One of the key questions raised in this experimental program is whether the unstarts are caused by projectile erosion due to aerodynamic and/or propellant combustion heating effects at hypersonic Mach numbers or if there are other gas dynamic processes causing the combustion wave to be disgorged ahead of the projectile. An intriguing finding of the ethane-fuel experiments is that there were no unstarts at all in superdetonative velocity regime. Granted these tests were at somewhat lower Mach number, but do these results imply that combustion must be initiated for hypersonic unstart to occur? Experiments with more refractory materials (e.g., nickel steel) and/or thermal insulation coatings and oxidizing barriers are very likely to establish if material properties are the main factor limiting the ability of the projectiles to cruise at hypersonic velocities greater than the CJ speed..

5 Summary

Titanium-alloy projectiles were launched into reactive propellants at 21 bar fill pressure with entrance Mach numbers ranging from 5.5 to 6.6 to investigate the operating characteristics of the shock-induced combustion propulsive cycle. Positive acceleration was observed in the Mach range of 5.5 – 7 (1.7 – 2.1 km/s) for distances of up to 6 meters in $1.5CH_4+2O_2+XCO_2$ propellant with $2.8 < X < 8$. Experiments with ethane-fueled propellant in the Mach number range of 5.5 – 6.1 found that projectiles would either experience a wave fall-off or cruise at relatively constant velocity without unstart. Significant projectile acceleration was not observed at superdetonative velocity in this propellant. Effective thrust in a shock-induced combustion-like propulsive mode was unequivocally demonstrated; however, more experimentation is necessary to determine whether it was propellant combustion phenomena or the effects of aerodynamic heating that limit the peak velocity to which a projectile can be accelerated.

References

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