JOURNAL OF PROPULSION AND POWER
Vol. 14, No. 6, November–December 1998

Ram Accelerator Operating Limits, Part 1: Identification of Limits

A. J. Higgins,* C. Knowlen,† and A. P. Bruckner‡
University of Washington, Seattle, Washington 98195

Operational limits of the thermally choked ram accelerator are investigated. A quasisteady, one-dimensional model of the ram accelerator predicts it should be able to operate when the projectile Mach number is sufficient to maintain supersonic flow past the projectile throat and the heat release is sufficient to stabilize a normal shock upon the projectile body, but not enough to drive the shock over the projectile throat. These limits to operation can be expressed as relations of Mach number and heat release Q, and together they define a theoretical envelope of operation in the Q–M plane. The corresponding experimental envelope was investigated by injecting projectiles at different Mach numbers into methane/oxygen/nitrogen and hydrogen/oxygen/methane mixtures at 25 and 50 atm, respectively. The results indicated a broad range of mixtures that were able to accelerate the projectile through the Chapman–Jouguet (CJ) detonation speed of the mixture. In the more energetic mixtures, the normal shock wave surged forward and immediately unstarted the projectile as it entered the test section. Unstarts were also observed when the projectile was accelerated beyond the CJ detonation speed, but because of the projectile's long in-tube residence time, these unstarts are believed to have been structural, not gasdynamic in nature.

Introduction

THE ram accelerator is a novel hypervelocity launcher in which a projectile is fired at supersonic speeds into a tube filled with a propellant of premixed fuel and oxidizer.[1,2] The projectile ignites the propellant as it passes, generating a high base pressure that accelerates the projectile. The details of the flow around the projectile are similar to a conventional ramjet, with the stationary tube replacing the cowling and a projectile performing the functions of the centerbody in a ramjet. Unlike a ramjet, however, the projectile carries no fuel, and the energy is stored entirely in the launch tube itself in the form of premixed fuel and oxidizer (usually methane, oxygen, and diluent gases). Because the propellant is distributed along the launch tube, unlike a conventional gun, the projectile can be efficiently accelerated to very high velocities, theoretically as high as 7–9 km/s. The propellant mixture can be varied along the launch tube to control both the in-tube Mach number and acceleration history. The potential of hypervelocity launching with a tailored acceleration history and ease of scaling has made the ram accelerator a promising candidate for applications ranging from hypersonic flow research[3,4] to direct launch to orbit.[5,6]

Since research on the ram accelerator began at the University of Washington (UW) in 1983, several modes of propulsion have been suggested.[1,2] The emphasis of experimental work to date has been on the subdetonative, thermally choked mode (Fig 1).[7] This mode has successfully accelerated 50–110 g projectiles to velocities approaching 3 km/s in the 38-mm-bore, 16-m-long UW ram accelerator facility. In this mode, the combustion is stabilized behind the blunt base of the projectile after the flow has been rendered subsonic by a series of shock waves. The shock system is stabilized on the projectile via thermal choking in the full tube area behind the projectile. A mixture that is too energetic will force the shock system ahead of the projectile throat, resulting in an unstart and subsequent projectile deceleration. (An unstart refers to the condition where the flow past the projectile throat is no longer supersonic and a normal shock is driven in front of the projectile.) As the projectile is accelerated in the thermally choked propulsive mode, the shock system recedes back along the body and thrust decreases. In theory, for a projectile whose base tapers to a point, the shock system will recede to occupy the full tube area and cease to provide thrust when the projectile reaches the Chapman–Jouguet (CJ) detonation speed of the mixture.[1]

In practice, it is found that the projectile can continue to accelerate as it passes through the transdetonative velocity regime.[2] This unexpected experimental finding is believed to result from supersonic combustion occurring on the projectile body and an unchoking of the flow behind the projectile (Fig. 1). Transdetonative operation allows the projectile to accelerate to superdetonative speeds, where again, various propulsive modes are possible. Superdetonative operation can also be initiated directly from subdetonative operation by using stages of propellants with different detonation speeds. One superdetonative mode of particular interest involves igniting the flow via an oblique detonation wave, in which case the flow remains supersonic and the heat release occurs entirely in the annular region between the projectile and tube wall (Fig. 1).

While considerable effort has been directed at predicting the performance of these various modes, little work has been done to determine their operational limits. Moreover, the conditions under which the combustion process is stabilized on the projectile, will overtake the projectile, or fall off the projectile base, are poorly understood. This paper represents an investigation motivated by the need for an improved understanding of the gasdynamic limits to the operation of the ram accelerator, particularly in the subdetonative and transdetonative regimes. Systematic experimental investigations of the heat release values and Mach numbers that will allow ram accelerator operation have been carried out in methane/oxygen/nitrogen- and hydrogen/oxygen/methane-based propellant mixtures at 25- and 50-atm initial pressure, respectively.

Received Sept. 2, 1996; revision received April 22, 1997; accepted for publication April 25, 1997.

*Graduate Research Assistant, Department of Aeronautics and Astronautics; currently Postdoctoral Research Fellow, Department of Mechanical Engineering, McGill University, Montreal, Quebec H3A 2K6, Canada. Member AIAA.

†Research Scientist, Department of Aeronautics and Astronautics. Senior Member AIAA.

‡Professor and Chair, Department of Aeronautics and Astronautics. Fellow AIAA.

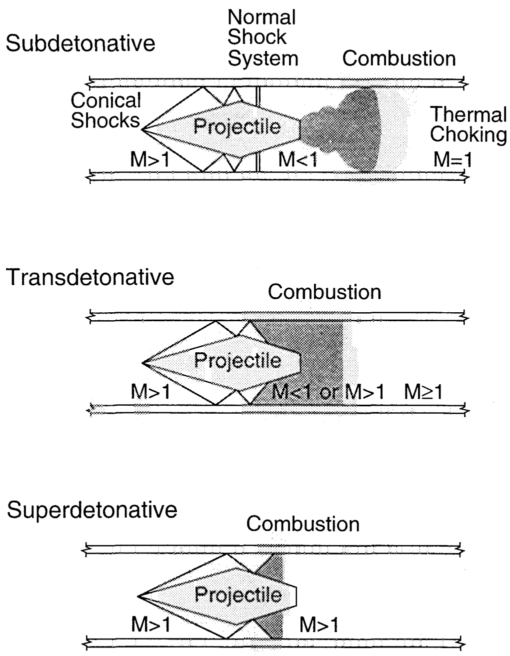

Fig. 1 Flowfields associated with different regimes of ram accelerator operation.

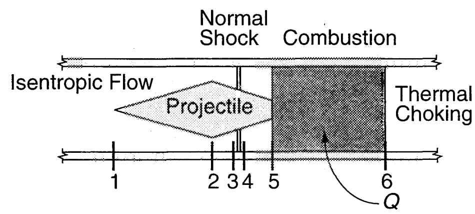

Fig. 2 One-dimensional model of the thermally choked ram accelerator flowfield.

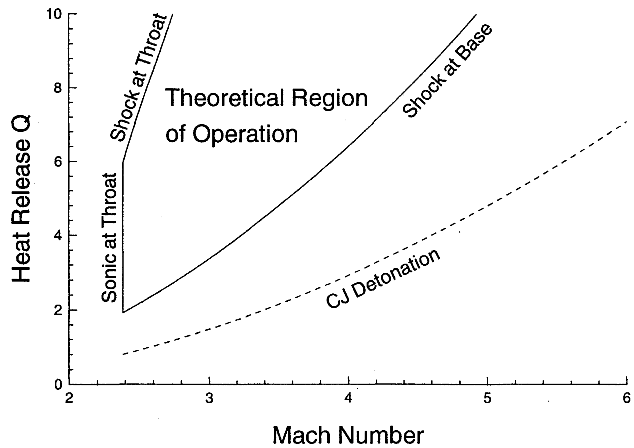

Fig. 3 Theoretical operational envelope of the thermally choked ram accelerator.

Theoretical Considerations

Zero-Dimensional Thrust Model

Once the assumption of steady thermally choked flow in the full tube area behind the projectile has been made, the heat release of combustion and the thrust on the projectile are uniquely determined by the flow conditions upstream of the projectile and are independent of the details of the flowfield around the projectile. Such a zero-dimensional model (also known as a control volume or Hugoniot analysis of the ram accelerator) has proven remarkably accurate at predicting observed projectile accelerations for velocities less than 90% of the CJ speed.[2,8] This excellent agreement is the validation of the assumption of thermal choking. The zero-dimensional model for thrust does nothing, however, to predict the ability of the ram accelerator to operate within a given mixture or at a particular velocity. This is to say, if the ram accelerator projectile successfully stabilizes the combustion process, the control volume analysis accurately reproduces its performance, but it will not be able to determine if the projectile can successfully accelerate at all. This situation is analogous to the CJ criterion of detonations, which predicts detonation properties such as propagation speed, but cannot predict the detonability limits of a mixture. To determine the limits of ram accelerator operation, the details of the flowfield must be examined.

One-Dimensional Flowfield Model

The simplest model of the thermally choked ram accelerator flowfield treats the flow over the projectile as isentropic, except for a single normal shock (Fig. 2). In reality, a single shock is unlikely; the flow more closely resembles the complex system of normal and oblique shocks that arise from shock-boundary-layer interactions.[9,10] This shock is stabilized on the body by thermal choking of the flow in the full tube area behind the projectile. The combustion behind the projectile is modeled as Rayleigh flow, i.e., constant-area heat addition. Beyond the thermal choking plane, an unsteady expansion is assumed to occur. The normal shock on the projectile body is free to move in response to changing upstream and downstream conditions. As the projectile accelerates, this shock recedes until it reaches the base of the projectile. If the projectile base were tapered to a point, the normal shock would eventually reach the full tube area as the projectile is accelerated to the CJ detonation speed. This condition results in a cessation of thrust, making the CJ speed the maximum theoretical velocity of thermally choked operation, which concurs with the results of the zero-dimensional thrust model mentioned earlier.

Such a model imposes three limits on ram accelerator operation. First, the projectile must maintain a certain minimum Mach number (approximately Mach 2.5 for the projectile geometries used in this investigation) to keep the flow supersonic past the projectile throat (station 2 in Fig. 2). Below this Mach number, the flow will choke on the projectile nose cone, resulting in an unstart. Second, a certain maximum is imposed on the heat release of the mixture, beyond which the normal shock is disgorged from the throat, also resulting in an unstart. Finally, a certain minimum heat release is required to keep the normal shock wave from falling off the projectile base. All three of these limits can be expressed in terms of the Mach number of the projectile and the heat release of the propellant mixture (along with the thermodynamic properties of the gaseous propellant) by using the standard relations of one-dimensional gasdynamics.[9] For example, to determine the shock-at-throat limit, the flow of a given Mach number is isentropically compressed to the projectile throat, where the normal shock relations are applied, then the flow is isentropically expanded back to the full tube area, where the amount of heat addition required to choke the flow behind the projectile is computed. For a given projectile throat-to-tube and base-to-tube area ratio, these relations define a theoretical region of operation, or operational envelope, for the ram accelerator. (The area of the fins is neglected in computing the base area.) This envelope, for the projectile geometry used in this investigation, is shown in a plot of heat release Q vs the projectile Mach number in Fig. 3, along with a curve indicating the dependence of the CJ Mach number on Q. Here, Q is the heat release of combustion nondimensionalized by the upstream temperature and constant pressure heat capacity, $Q = \Delta q/(c_{p1}T_1)$. Again, for a projectile whose base tapers to a point, the shock-at-base limit corresponds to the CJ relation. For Fig. 3, the gas is assumed to be calorically perfect with a specific heat ratio $\gamma = 1.4$. Hence, in this example, the combustion is treated as external heat addition to a perfect working fluid. Modifications can be included into this one-dimensional model to account for the changing thermodynamic properties of the gas as functions of chemical equilibrium, but they result in only minor differences to the curves plotted in Fig. 3. Also, including total pressure losses for the diffuser and blunt projectile base does not affect the qualitative nature of this envelope.[11] This envelope bounds a large region of Mach number and heat release values, indicating that a potentially wide range of operating conditions might be realized.

The one-dimensional flowfield model is a convenient way to examine the influence of various nonideal effects, such as precombustion on the projectile. For example, if we arbitrarily prescribe 10% of the total heat release to occur at the projectile throat, the effect of precombustion on the theoretical envelope is shown in Fig. 4. Of course, determining the actual heat release caused by premature ignition would require detailed chemical kinetic and flow considerations. Note that the minimum Mach number for operation at both the sonic-at-throat and shock-at-throat limits has been increased. This is to say, precombustion has the effect of driving the flow toward sonic, allowing the area contraction at the throat to more easily choke the flow, causing an unstart. Precombustion also moves the normal shock forward, allowing it to be disgorged from the throat at lower values of heat release, also causing an unstart. The fact that both of these unstart mechanisms can be relevant, even when the projectile is above the ideal minimum starting Mach number, will be important when the nature of the experimentally observed limits is investigated.[12]

This modeling shows that the envelope is extremely sensitive to the location of any precombustion. For example, if 10% of the total heat release were prescribed on the tip of the nose cone at the full flight Mach number, the effect on the sonic-at-throat and shock-at-throat limits is much more significant than as shown in Fig. 4. Alternatively, precombustion occurring in the subsonic flow on the projectile body has only a minimal effect on the operational limits.[13] This sensitivity to the location of any precombustion is a result of the fact that total pressure losses caused by heat addition go as the square of the Mach number.[9]

This theoretical model of operation can also be used to examine the effects of changing the projectile geometry. For example, if the projectile's throat diameter is made smaller, the annular area between the projectile and tube wall increases. This change decreases the minimum starting Mach number, shifting the sonic-at-throat line to the left. It also decreases the heat release required to drive the normal shock over the projectile throat, lowering the shock-at-throat line.[13] A reduction in throat diameter might be useful if operation at Mach numbers less than Mach 3 is desired, but such a change might be compromised by requiring a reduction in the energy content of the mixture.

Comparison to Experiment

Although these theoretical considerations suggest the ram accelerator has a wide envelope of operation, experimentally it is unable to access most of the operation region that this simple model predicts. In practice, the ram accelerator has rarely demonstrated operation in mixtures with $Q > 6$. The ram accelerator in the thermally choked mode usually operates at conditions under which a normal shock would have fallen off the base of the projectile. That is, the ram accelerator is typically operated in the region of Fig. 3 with $3 < Q < 6$ and $3 < M < 6$.

While operation in more energetic mixtures would obviously be desirable, attempts to do so usually result in immediate unstart when the projectile enters the mixture. This is a very violent phenomenon in which a normal shock is disgorged from the throat of the projectile, often developing into an overdriven detonation and causing a pronounced deceleration of the projectile. Figure 5 shows an unstart in a series of pressure traces taken from transducers mounted 40 cm apart along the tube wall. The pressure traces are synchronized with the passage of the projectile throat at $t = 0$. The projectile length is shown relative to the time scale of the data. Trace a indicates nominal ram accelerator operation: the pressure peaks near the throat are the oblique shocks of the nose cone reflecting off the tube wall, and the high-pressure region behind the projectile is supported by combustion. The remaining traces (b–e) show the progression of an unstart as a large pressure wave (pressure ratio ~50) developing on the projectile and propagating down the tube, in front of the projectile. The total elapsed time for these records is ~1 ms.

Unstarts are also observed after the projectile has been accelerated for several meters in a given propellant mixture. It is unclear whether these unstarts are also a result of gasdynamic phenomena, or are a result of structure failure caused by extensive heat transfer to the projectile and erosion of its fins. The time scale of the unstart (less than a millisecond) and the fact that in most cases the projectile is destroyed makes determining the exact cause of unstarts challenging.

The unstart of projectiles, which limits the operation of the ram accelerator, is the subject of the experimental investigation presented here. The experimental region of operation was mapped as a function of heat release and Mach number for methane/oxygen/nitrogen and hydrogen/oxygen/methane mixtures. A subsequent paper[12] investigates the cause of these projectile unstarts, i.e., whether they are gasdynamic or structural in nature.

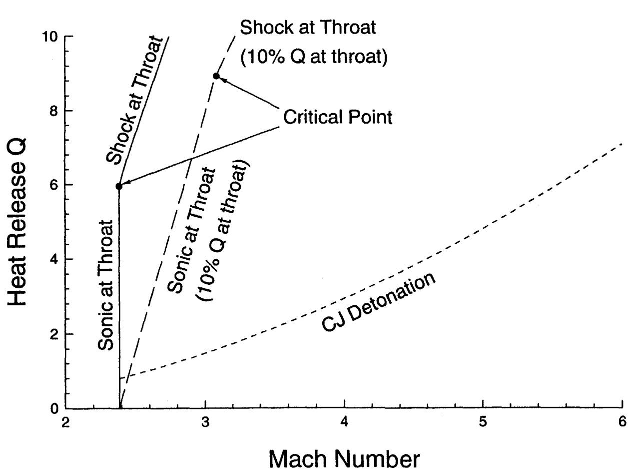

Fig. 4 Effect on the operational envelope of precombustion at the projectile throat. Critical points note a change in the unstart mechanism.

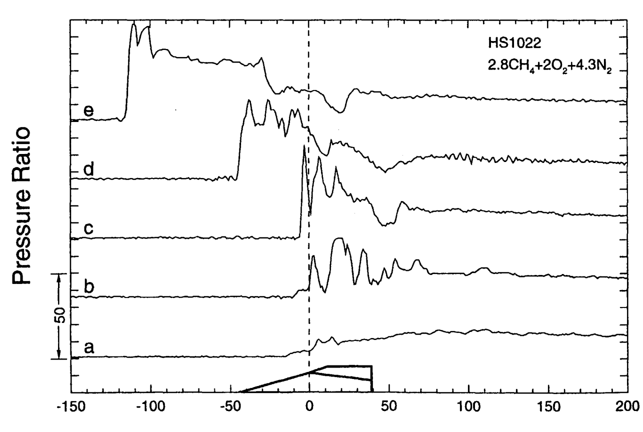

Fig. 5 Evolution of an unstart as seen by pressure transducers mounted on the tube wall.

Facility

A 38-mm-bore, 6-m-long single-stage light-gas gun is used to accelerate the projectile to the required supersonic entrance velocity for the ram accelerator (usually Mach 3). The 16-m-long ram accelerator test section consists of eight 2-m-long, high-strength steel tubes having a bore of 38 mm and an o.d. of 102 mm. Thin Mylar diaphragms close off each end and separate different propellant mixtures in multistage experiments. Instrumentation ports are spaced at 40-cm intervals along the test section. The primary instrumentation is piezoelectric pressure transducers, for monitoring the impingement of shock waves on the tube wall, and electromagnetic (EM) sensors, for tracking an annular magnet in the projectile throat. Both of these instruments provide independent means of tracking the projectile's velocity and identifying unstarts.

The projectiles are fabricated in two hollow pieces (nose and body) that thread together at the throat. Fins are required to center the projectile in the tube. The projectiles used in the low-pressure (25-atm) methane/oxygen/nitrogen mixtures had four fins, were fabricated from magnesium alloy (ZK60 AT5), and had a mass of 64 g (Fig. 6). The projectiles used for the high-pressure (50-atm) hydrogen/oxygen/methane experiments had five fins, were fabricated from aluminum alloy (7075 T6), and had a mass of 76.5 g. The change from magnesium to aluminum alloy for the second series of experiments was influenced by the identification of a material limitation for magnesium projectiles in related studies.[12] The tube-to-base area ratios of the four- and five-fin projectiles were kept constant by thinning the fins (Fig. 6). The change to five fins was motivated by prior experiments, which showed more pronounced transdetonative performance with five-fin projectiles in single-stage experiments.[14]

Mixture Selection

The theoretical operational envelopes developed earlier in this paper are exclusively functions of the projectile Mach number and mixture heat release. To explore the corresponding experimental envelope, the heat release must be varied in a systematic way. Specifying the heat release, however, does not uniquely specify the chemistry of the propellant mixture. The numerical value of heat release Q is computed using a chemical equilibrium code. With the assumption of thermal choking behind the projectile, this value is solely a function of the projectile Mach number and the initial mixture composition, temperature, and pressure. The value of Q is identical to that used in the zero-dimensional thrust model and is independent of the details of the flowfield. For example, a Mach 4 flow of a stoichiometric mixture of oxygen and methane ($CH_4 + 2O_2$) at 25 atm has a Q value of 19.8. Now, suppose a mixture with a Q value of 5.0 is to be explored. Excess fuel could be added to dilute the mixture, yielding the mixture $6.3CH_4 + 2O_2$, or an inert gas like nitrogen could be added, giving $CH_4 + 2O_2 + 15N_2$. Hence, to uniquely relate the propellant mixture to a value of heat release, the choice of mixture must be constrained in some way.

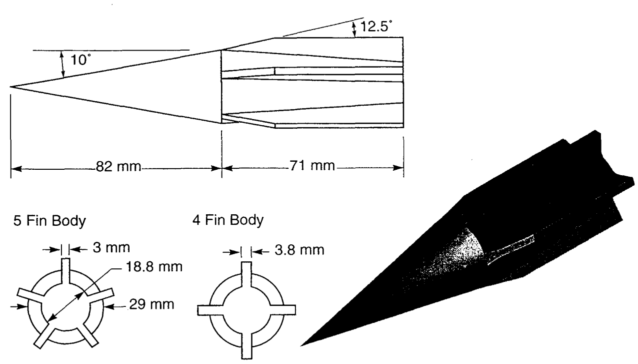

Fig. 6 Ram accelerator projectiles.

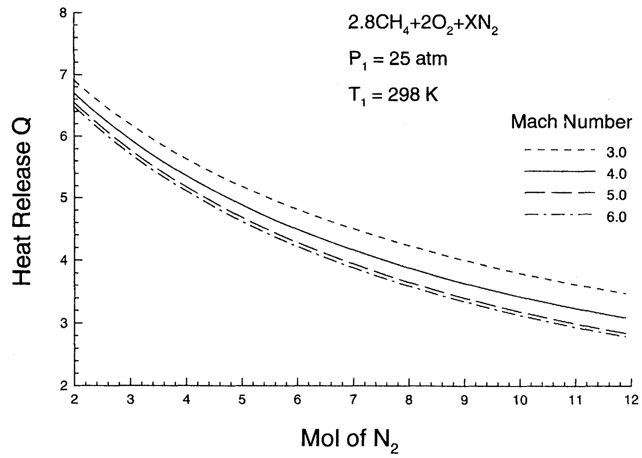

Fig. 7 Thermally choked nondimensional heat release ($Q = \Delta q/c_{p1}T_1$) as a function of nitrogen dilution for various projectile Mach numbers.

Nitrogen Diluted Mixtures

For the first set of results that will be presented in this paper, the fuel equivalence ratio was fixed to 2.8 while varying the amount of nitrogen dilution; i.e., $2.8CH_4 + 2O_2 + XN_2$. This mixture class was selected because the $2.8CH_4 + 2O_2 + 5.7N_2$ propellant mixture has proven a reliable first stage in the operation of the UW facility and routinely exhibits transdetonative performance. This mixture was used as an initial starter stage for all of the experiments presented in this investigation. The value of thermally choked heat release Q, as predicted by a chemical equilibrium code,[11] is shown in Fig. 7 as a function of nitrogen dilution at various projectile Mach numbers. The heat release decreases with increasing projectile Mach number for a given mixture because of the increasing static temperature at the plane of thermal choking, resulting in greater dissociation losses. This decrease in Q is visible in plots of experimental data in the Q–M plane as a slight downward slope of the experimental curve.

It should be emphasized that the value of Q is the nondimensional heat release for thermally choked flow. Since the flow cannot be thermally choked in the full tube area behind the projectile in transdetonative and superdetonative operation while producing positive thrust, this value of Q is not the actual heat release in those cases. Obviously, in cases where the flow did not ignite, Q would be meaningless. Nonetheless, a value of Q is ascribed to these experiments as if the flow was achieving chemical equilibrium and thermally choking behind the projectile. This provides a consistent and qualitative measure for comparing the effective heat release of different chemistries under similar flow conditions.

Methane Diluted Mixtures

The ability of the ram accelerator to be staged with multiple propellant mixtures in a single experiment allows it to bypass the velocity limitations of a particular mixture. As will be shown in the experimental results section, the methane/oxygen/nitrogen class of the starting mixture discussed earlier is limited to approximately 120% of the CJ speed, or 2.2 km/s. This velocity can be exceeded if the projectile first transitions to a mixture with a higher acoustic and detonation speed. This procedure also offers the advantage that by keeping the in-tube Mach numbers low, the aerodynamic heating of the projectile is greatly reduced.

The standard first-stage mixture ($2.8CH_4 + 2O_2 + 5.7N_2$) accelerates the projectile to a velocity of 1.5 km/s by the end of the first 2-m-long segment of tube at 50-atm initial pressure. This joint between tubes is the first convenient place to begin a second stage. If projectile acceleration is to be maximized and in-tube heat transfer is to be minimized, the projectile

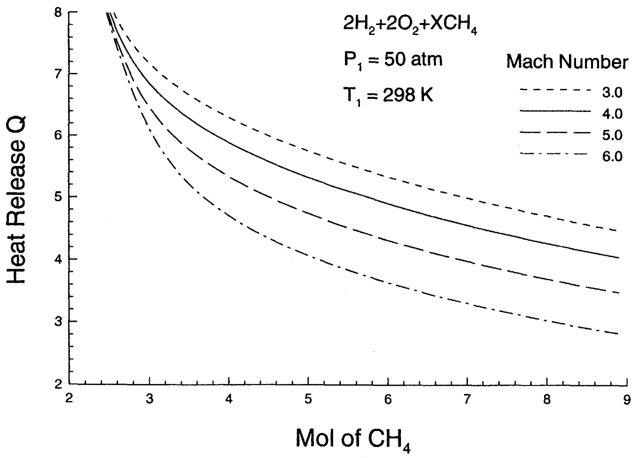

Fig. 8 Thermally choked nondimensional heat release ($Q = \Delta q/c_{p1}T_1$) as a function of methane dilution for various projectile Mach numbers.

should enter the next stage at as low a Mach number as feasible, while still maintaining a sufficient margin above the ideal isentropic starting Mach number. Mach 3 is a convenient reference. This implies that any propellant with a sound speed of ~500 m/s would be a candidate second stage ($4.5CH_4 + 2O_2 + 2He$ has been used extensively in the past[7]). A mixture of $2H_2 + 2O_2 + XCH_4$ has the property that the effective mixture molecular weight and sound speed (499 m/s) hardly varies as the methane content is changed. Thus, the excess methane makes an ideal knob on the mixture heat release without affecting the thermodynamic properties. The mixtures are formulated on the fuel-rich side ($X > 0.5$), so that methane plays the role of both a fuel, by increasing the fuel equivalence ratio from lean to rich, and a diluent to reduce the energy content.

The heat release parameter Q as a function of XCH_4 is shown in Fig. 8 for several Mach numbers. Notice that the value of Q is more acutely influenced by the projectile Mach number in methane-diluted mixtures than in the nitrogen-diluted mixtures shown in Fig. 7. This sensitivity will be seen as a more pronounced slope of the experiments in the Q–M plane for methane-diluted experiments. With the use of Figs. 7 and 8, the mixture composition can be related to the heat release at a given projectile Mach number for the experiments presented in this paper.

Experimental Procedure

The process by which the combustion wave is initiated and stabilized on the projectile is a complicated and unsteady interaction between the projectile and an obturator that occurs upon impact with the first stage of ram accelerator propellant.[15,16] Since the purpose of these experiments was to determine the limits of ram accelerator operation, as opposed to starting, the experiments had to be carefully isolated from the combustion initiation process. To achieve this, the first 2 m of the ram accelerator were filled with the same $2.8CH_4 + 2O_2 + 5.7N_2$ mixture for all experiments. This mixture consistently initiates and stabilizes the combustion process behind the projectile. If the entire ram accelerator were filled with this mixture, it would accelerate a magnesium projectile to approximately 2000 m/s, where an unstart would occur. Hence, this mixture formed the control in the investigation of gasdynamic limits to operation.

Projectile operation is believed to be independent of the combustion initiation process after traveling 2 m in the starter stage. The projectile then transitions into the test mixture, as shown schematically in Fig. 9. For the nitrogen-diluted mixtures, the fill pressure for both starter and test stage was 25 atm. The projectile left the gas gun at 1130 ± 25 m/s. After initiating combustion and accelerating for 2 m, it entered the

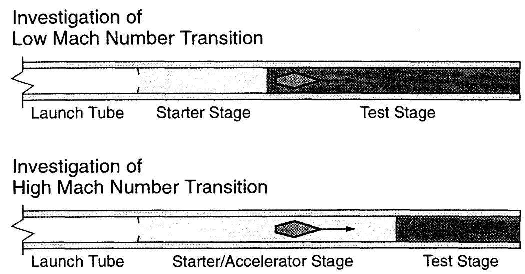

Fig. 9 Experimental configurations used in investigating operational limits of the ram accelerator.

test mixture at 1390 ± 20 m/s. In later experiments, the starter stage was lengthened to 4 m to examine the effect of transitioning into the test mixture at higher Mach numbers (Fig. 9). Experiments in methane-diluted mixtures were conducted with the fill pressure at 50 atm for all stages. The projectile exited the gas gun at ~1150 m/s and transitioned from the starter stage to the test mixture at 1530 ± 25 m/s. Higher velocity transitions were also performed for this class of mixture by using intermediate stages between the starter and test stages.

The projectile was tracked down the length of the test section via EM sensors and pressure transducers until unstart occurred. The velocity of the projectile was measured to within ±10 m/s, and the location of the unstart was identified to within ±0.2 m. The velocity–distance profiles presented in this paper are actually higher-order (4–9th) polynomial curve fits to the first-order finite difference of the position–time history of the projectile, as given by the EM sensors. Samples drawn from the ram accelerator tube immediately before firing were analyzed via gas chromatography to ensure the correct propellant mixture was used. The gas-handling system allows for the mixture to be varied in an accurate and reproducible manner to within ±0.1 mol in both the $2.8CH_4 + 2O_2 + XN_2$ and $2H_2 + 2O_2 + XCH_4$ classes of propellant.

Results

Nitrogen-Diluted Mixtures

For the experiments conducted in $2.8CH_4 + 2O_2 + XN_2$, the nitrogen dilution was varied from 3 to 12 moles, or 40 to 70% by volume, which allowed limiting phenomena to be observed from immediate unstart to combustion wave falloff. The results of these experiments, showing the projectile's velocity as a function of its position in the test section, are presented in Fig. 10. The projectiles exhibited similar accelerations in the starter stage, but as they entered the test section their velocity histories spread out according to the mixture energy content. A detailed analysis of the observed accelerations is presented in Refs. 17 and 18; our emphasis here remains on the limits to operation, rather than performance. Two of the most dilute mixtures (9.0 and $12N_2$) were unable to support combustion and the normal shock wave system fell off the projectile, leaving the projectile to decelerate as it coasted supersonically out the tube. All other mixtures exhibited at least some acceleration in the test section, except for the most energetic, which promptly unstarted.

As a general rule, the less energetic a propellant mixture, the farther the projectile drove into the test section before unstart. The ultimate velocity, however, exhibited a maximum with respect to the amount of dilution. This observation becomes clearer when the data are plotted in the Q–M plane (Fig. 11). This figure is a combination of experiment and theory; the experimentally measured projectile Mach number is plotted against the computed value of thermally choked heat release. The theoretical CJ detonation wave relationship between heat release Q and Mach number of propagation is also shown. Most of the mixtures exhibited at least some transdetonative operation, meaning the experiments operated to the right of the CJ curve in Fig. 11.

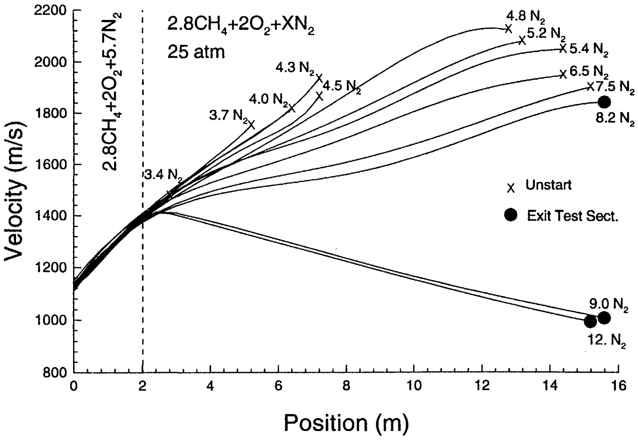

Fig. 10 Velocity–distance data for Mach 3.8 transitions into mixtures with variable nitrogen dilution.

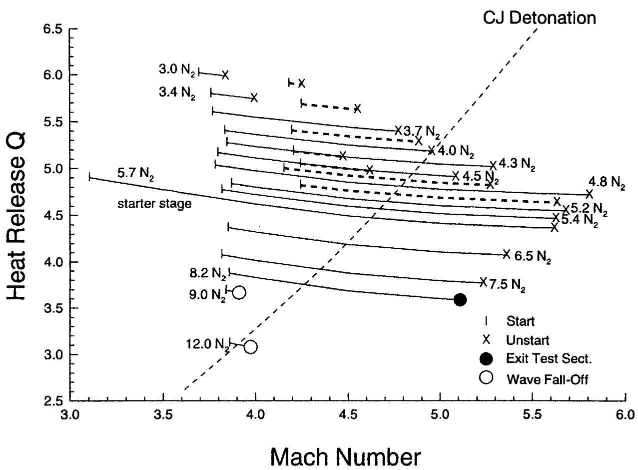

Fig. 11 Results of nitrogen-diluted mixtures plotted as heat release vs Mach number. Thick dashed lines indicate experiments with higher transition velocities.

The experiment using the $2.8CH_4 + 2O_2 + 4.8N_2$ propellant mixture exhibited the maximum projectile velocity in this series. Although the projectiles in more diluted mixtures (5.2–7.5N_2) traveled farther into the test section before unstarting, the reduced energies of these mixtures compromised their acceleration. Hence, these projectiles actually unstarted at lower velocities as the amount of diluent increased. The longer history of heat transfer and projectile wear makes it difficult to ascribe these unstarts to pure gasdynamics. The more energetic mixtures plotted in Fig. 11 (4.5–3.0N_2) unstarted earlier in the test section, with less than 8-m total travel. The fact that these projectiles unstarted early in the experiment, despite their reduced history of heat transfer and fin erosion, strongly suggests that these unstarts are the result of pure gasdynamic or combustion phenomena. The most energetic mixtures (3.0 and 3.4N_2), which unstarted within the first meter of transition, appear to bound the maximum heat release for ram accelerator operation in this class of mixture.

Attempts to operate in more energetic mixtures were made by increasing the velocity at which the projectile transitions from the starter to the test stage (Mach 4.2 instead of 3.8). These experiments were motivated by the theoretical considerations presented earlier, which suggest that any value of Q should support operation if the projectile enters at a high enough Mach number (Fig. 3). These experiments are also shown on the Q–M plot in Fig. 11 as thick dashed lines (no velocity–distance data are shown for these experiments). Although some scatter is seen in the more energetic mixtures, for the most part, the observed limits appear to concur with those found in the lower Mach number transition experiments. This agreement reinforces the idea that the limit on mixture heat release is primarily a gasdynamic phenomenon. Additional details on these experiments are given in Refs. 13 and 19.

Methane-Diluted Mixtures

In these experiments, XCH_4 is varied from 4.8 to 9 (55 to 70% by volume). The velocity–distance profiles for the methane-diluted experiments are shown in Fig. 12. As in the prior experiments, the velocity histories agree through the first stage and only spread out in the test section as the diluent concentration is varied. The least energetic of these mixtures (9.0CH_4) was unable to support combustion, and the driving shock system fell off, leaving the projectile to decelerate until the diffuser unstarted (Mach 2.6). The next more energetic mixture (7.0CH_4) was able to support a combustion wave, which accelerated the projectile over the entire length of the ram accelerator tube, exiting at 2070 m/s. The remaining experiments all terminated with unstarts in the test section. As previously observed, the unstarts occurred earlier in the test section as the mixture energy increased. The maximum velocity achieved, however, increased as the methane content was reduced to the point where the combustion wave was no longer able to be contained on the projectile. Although the unstart velocity was not always a smooth function of the methane dilution, the observed accelerations increased monotonically with decreasing methane content, giving confidence that the mixture energies were being consistently varied.

The limits to operation become clearer when the results are plotted in the Q–M plane, as shown in Fig. 13. Note that the

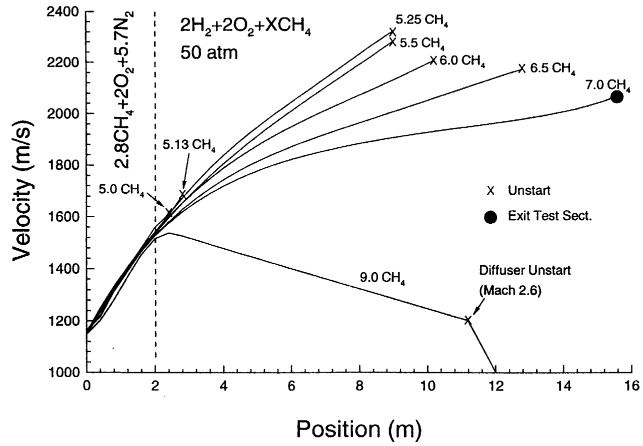

Fig. 12 Velocity–distance data for Mach 3.4 transitions into mixtures with variable methane dilution.

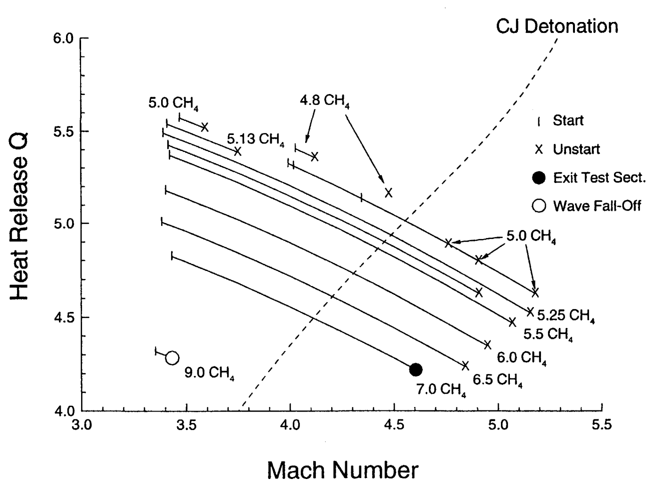

Fig. 13 Results of methane-diluted mixtures plotted as heat release vs Mach number.

maximum projectile velocity was obtained by using the most energetic propellant that would sustain ram accelerator operation. This differs from the results of the nitrogen-diluted mixtures, where the maximum velocity obtained was a point between the maximum and minimum energetics (Fig. 11).

As with the nitrogen mixtures discussed earlier, attempts were made to operate with even less methane dilution by an even higher transition velocity. An intermediate stage using a proven hydrogen/oxygen/methane mixture, e.g., $2H_2 + 2O_2 + 7CH_4$, was used to accelerate the projectile to the desired test velocity. As seen in Fig. 13, increasing the transition Mach number to 4 did allow operation in a less dilute mixture ($5.0CH_4$). The heat release value Q, however, was not any greater for these experiments. Nor did a higher transition Mach number permit operation in an $4.8CH_4$ mixture, which promptly unstarted at every attempted entrance velocity. Additional details on these experiments are given in Ref. 20.

Discussion

A number of similarities can be observed between the experiments performed with nitrogen dilution at 25 atm and methane dilution at 50 atm. For one, to sustain combustion on the projectile body, Q values of approximately 4 and 4.5 are required for the nitrogen and methane diluted experiments, respectively. Once the energy content is sufficient to sustain ram acceleration, the mixtures show a broad range of Q values that will allow the projectile to reliably accelerate through the CJ speed and exhibit transdetonative performance.

Both classes of mixture allow the projectile to accelerate farther into the tube as the energy content is reduced by increasing the diluent concentration. The maximum velocity, however, is obtained using a mixture which is between the wave falloff and immediate unstart cases. For mixtures more dilute than the maximum velocity experiment ($5.2–8.2N_2$ for nitrogen-diluted, and $5.25–7.0CH_4$ for methane-diluted experiments), the unstarts that bound operation form a line that is remarkably parallel to the CJ detonation curve in the $Q–M$ plane. At first, this limit may not seem an unexpected result because the CJ speed is the theoretical maximum operating velocity of thermally choked operation. This theoretical limit, however, is a limit on thrust, not an unstart mechanism. The projectile should theoretically accelerate to the CJ speed and coast at constant velocity, not unstart.

The line of unstarts parallel to the CJ curve is also suspect because it shows projectiles at a given Mach number, say Mach 5.25, unstarting in mixtures with lower energy content while continuing to accelerate in more energetic mixtures. If anything, higher heat release values and energy content should aggravate any gasdynamic unstart mechanism, providing an upper bound on the allowable Q values. Lowering the energy content while maintaining the same Mach number may cause cessation of thrust, but not an unstart. What is observed in Figs. 11 and 13, however, is the line of unstarts parallel to the CJ detonation relation that appear to bound a minimum heat release. This fact strongly suggests that the unstart mechanism in this case is not gasdynamic, but a structural failure of the projectile because of its relatively long residence time in the tube. This hypothesis would explain why a more energetic mixture can accelerate the projectile to higher velocities: it is able to accelerate the projectile more quickly, before it is destroyed by heat transfer or fin erosion.

The unstarts discussed so far all occurred after 8 m of travel in the ram accelerator, reinforcing the suspicion that they are affected by structural and material factors. This hypothesis has since been confirmed by repeating certain experiments with a more rugged projectile material, such as titanium.[12] The unstarts that occur much earlier in the test section, then, should be the result of pure gasdynamic and combustion phenomena. Both mixture classes exhibit a maximum allowable heat release of $Q \sim 5.5$, beyond which the projectile will immediately unstart upon entering the test mixture. This is not surprising since a hot limit must exist at some point. For the methane-diluted experiments at 50 atm (Fig. 13), this limit occurs with heat release values just incrementally greater than that of the maximum velocity experiment.

For the nitrogen-diluted experiments at 25 atm (Fig. 11), mixtures more energetic than the maximum velocity mixture ($4.8N_2$), but less energetic than immediate unstart ($3.4N_2$), continue to establish ram accelerator drive for between 3–6 m, but unstart at lower than the peak velocity. The unstarts in these mixtures ($3.7–4.5N_2$) cannot be explained in terms of the idealized one-dimensional model presented earlier. That model predicts that once ram acceleration is established, the projectile should continue to accelerate, causing the normal shock to recede along the body and therefore reduce the potential for unstart. As seen in Fig. 3, the projectile should theoretically be able to operate at any value of Q, provided the initial Mach number is sufficiently high to stabilize the shock behind the throat. The experimental result for mixtures in the $3.7–4.5N_2$ projectile range that can start, accelerate, and then unstart while still retaining structural integrity implies an unstart mechanism that cannot be explained in the context of the one-dimensional theory. The nature of this unstart phenomenon, whether it is caused by precombustion on the projectile forebody or is a result of the normal shock being driven past the projectile throat, is the subject of a more detailed investigation.[12]

A stylized representation of the experimentally determined limits for the two classes of mixture investigated here is presented in Fig. 14. The operational envelope for the hydrogen/oxygen/methane experiments is shown to occupy a smaller, but similar, region in the $Q–M$ parameter space. The reduced region of operation could be the result of several factors. The higher pressure of these experiments could increase combustion kinetic rates, aerodynamic heating, structural stress, etc. The presence of hydrogen, with its increased flammability and kinetics rates, may also affect the energy limits for ram accelerator operation. Of course, the stylized limits depicted in Fig. 14 are specific to the projectile geometry and mixture classes used in this investigation.

While this investigation has identified these distinct limits of ram accelerator operation, the causes of these limits is the subject of further investigation.[12] The experimentally determined envelope in Fig. 14 is seen to occupy a different region and to be of a qualitatively different shape than the theoretical envelope of operation in Fig. 3. The one-dimensional flowfield model apparently cannot reproduce the mechanisms responsible for the observed unstarts. Reference 12 addresses this issue by considering whether the gasdynamic unstart is caused by precombustion choking the flow on the projectile forebody or is the result of the normal shock wave system surging past the

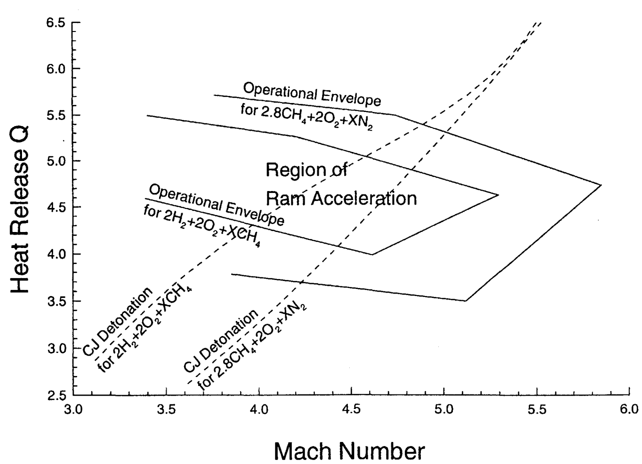

Fig. 14 Stylized operational envelopes for experiments in nitrogen- and methane-diluted mixtures.

projectile throat. Also addressed in Ref. 12 is the question of whether the suspected structural failure after long acceleration histories is the result of heat transfer to the nose cone or fin erosion on the tube wall.

Conclusions

By varying the amount of nitrogen or methane dilution, distinct limits to ram accelerator operation have been identified. A certain minimum heat release is required to maintain a combustion process stabilized on the projectile. A maximum heat release sets a limit beyond which the projectile will immediately unstart. Between these two, there is a wide range of dilution values that allow successful ram acceleration.

For the more dilute mixtures, the projectile drove farther into the tube before unstarting, but the longer in-tube residence time and history of heating and wear lend support to the idea that these unstarts were structural rather than gasdynamic in nature. As the dilution was decreased, the projectiles unstarted earlier in the tube, but actually achieved higher velocity owing to the higher energy content of the propellant mixture and resultant higher accelerations. As the propellant energy was increased beyond that of the maximum velocity mixture, unstarts occurred at lower and lower velocities, until unstart was immediate upon entrance to the test stage. The mechanism of these gasdynamic unstarts is not explained by the present one-dimensional flow field model.

The $Q-M$ plane is a convenient parameter space in which to investigate both theoretical and experimental limits to ram accelerator operation, in that it displays the two parameters of primary interest. Heat release Q represents the energy content of the propellant mixture, a parameter that should be optimized to obtain higher accelerations. High Mach number operation represents the velocity potential of a mixture, whereas the ability to operate at low Mach number implies more efficient, higher thrust operation with lower aerodynamic heating.

Acknowledgments

This work was supported in part by U.S. Army Research Office Grant DAAL03-92-G-0110 and Air Force Office of Scientific Research Grant F49620-92-J-0375. The assistance of John Hinkey with the gas chromatography, and of Akihiro Sasoh and Thomas Imrich with the laboratory experiments, is greatly appreciated. Malcolm Saynor machined the magnesium projectiles. 4-D Manufacturing, Inc., of Redmond, Washington, fabricated the aluminum projectiles.

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