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Ram Accelerators: Outstanding Issues and New Directions

Andrew J. Higgins
McGill University, Montreal, Quebec H3A 2K6, Canada

An assessment of the key issues affecting the thrust and maximum velocities that can be obtained in ram accelerators is presented. The regimes of ram accelerator operation (subdetonative and superdetonative) are discussed, and simple models for thrust are compared to experimental results and found to be satisfactory. The phenomena that are responsible for the operating limits of these modes of operation are explored, and potential solutions for overcoming these limits are discussed. In particular, the possibility that flow separation may cause unstarts in both the subdetonative and superdetonative ram accelerator is shown to explain qualitatively the experimentally observed limits. A potential remedy to the unstart problem that involves modifying the geometry of the ram accelerator tube is presented. The role of the projectile material, which may react with the oxidizing environment of the propellant, also has a significant effect on superdetonative operation. Techniques to address this problem are outlined. Other novel concepts, such as the use of an explosive-lined launch tube and the laser-driven ram accelerator, are discussed as well.

Nomenclature

A	=	area
$\mathcal{R}$	=	area ratio (tube area to throat area)
c_f	=	skin-friction coefficient
F	=	thrust
h	=	enthalpy
M	=	Mach number
p	=	pressure
Q	=	$\Delta q/c_p T_1$ (nondimensional heat release)
u	=	velocity
α	=	Mach angle
Δq	=	heat release
ρ	=	density
τ	=	viscous shear stress
χ	=	inert gas dilution

Subscripts

s	=	flow condition at boundary-layer separation point
1	=	flow conditions approaching projectile
2	=	flow conditions at projectile throat
6	=	flow condition exiting projectile control volume in thermally choked mode

I. Introduction

THE ram accelerator is a hypervelocity launcher in which a projectile travels through a tube pre-filled with a combustible mixture of gases.[1] The projectile, which resembles the centerbody of a conventional ramjet, compresses the gas mixture as it travels supersonically through the tube, and combustion of the gas is stabilized on or behind the projectile. The combustion results in a zone of high pressure acting on the base of the projectile, causing the projectile to accelerate. This zone of high pressure, which travels with the projectile and accelerates it continuously, allows the ram accelerator to overcome the velocity limitations of traditional guns[2,3] that are constrained by the expansion speed of the propellant gases.

The flowfield around the projectile is analogous to that of a ramjet (with subsonic combustion) or a scramjet (with supersonic combustion), as shown schematically in Fig. 1. No fuel is carried onboard the projectile; the combustible gases are premixed and filled into the launch tube before the passage of the projectile. Unlike a conventional ramjet flying through the atmosphere, the mixture of gases in the tube can have a varying acoustic speed, such that the in-tube Mach numbers are maintained over a range that maximizes thrust and minimizes in-tube aerodynamic heating of the projectile. When a combination of different propulsive modes (invoking both subsonic and supersonic combustion) are used, the projectile can accelerate continuously from in-tube Mach numbers of Mach 2 to 10. Depending on the acoustic speed of the gas mixtures used, this range of Mach numbers corresponds to projectile velocities from 600 to 8000 m/s. Typically, a conventional gun (gas gun, powder gun, etc.) is used as a prelauncher to accelerate the projectile to the minimum Mach number required for inlet starting. The upper velocity limit is imposed either by a thrust-equals-drag condition or by the intense aerodynamic heating of the projectile at hypervelocities.

The ram accelerator is a rather simple apparatus compared to other hypervelocity launchers (two-stage light gas guns, electromagnetic guns, etc.): In principle, the only equipment required is the launch tube, which needs only to contain the moderate driving pressures of the combustion zone that travels with the projectile, and the low-velocity prelauncher. This is in contrast to the pump tube of two-stage light gas guns, which must contain pressures that are typically orders of magnitude greater than the average driving pressure on the projectile, and the complex, pulsed power requirements of electromagnetic guns. The energy source used to accelerate the projectile in a ram accelerator, that is, a combustible mixture of gases, is located in the launch tube itself. This feature contributes to the ease with which the ram accelerator can be scaled to launch larger projectiles: As the launch tube diameter is increased, the amount of chemical energy available increases accordingly. Using the launch tube itself as the energy source reservoir means that the power regulation and management issues that complicate electromagnetic launchers, for example, railguns and coilguns, can be avoided. The ability to soft

Andrew Higgins has a B.S. in aeronautical and astronautical engineering from the University of Illinois in Urbana/Champaign. His Master's and Ph.D. degrees are from the University of Washington, Seattle, both in aeronautics and astronautics, where he worked on the original ram accelerator facility. Since 1997, he has worked in the Shock Wave Physics Group of McGill University, where he is currently an associate professor. His research investigates the dynamics of detonation in gaseous, heterogeneous, and condensed-phase media, with applications to aerospace propulsion, hypervelocity launchers, and achieving extreme states of matter.

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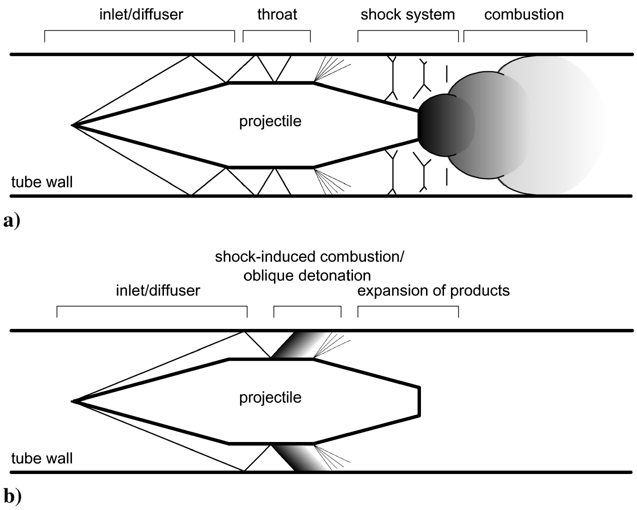

Fig. 1 Schematic of a) subdetonative, thermally choked ram accelerator flowfield and b) superdetonative ram accelerator.

launch large-scale projectiles to hypervelocities makes the ram accelerator suitable for applications such as simulating hypervelocity impact, aeroballistic testing,[4,5] defense (long-range bombardment, missile defense, etc.), and ground-based direct launch to orbit.[6–9]

In addition to its utility as a hypervelocity launcher, the ram accelerator is also of interest as a tool to explore the reactive fluid dynamics of hypervelocity airbreathing propulsion and, in particular, scramjets. Although the ram accelerator projectile is typically much smaller in size than a prototypical scramjet, the fact that it operates at much higher fill pressures means that the fluid dynamics of the ram accelerator closely approximate those of a scramjet in atmospheric flight. For example, a 15-cm-long ram accelerator projectile operating in the superdetonative regime (in-tube Mach numbers from 6 to 10) with 25-atm initial fill pressure experiences the same range of Mach number and Reynolds number in the combustor section of the projectile as would a scramjet with a 1-m-long combustor flying in the range from Mach 8 to 14 at a 10-km altitude. The larger initial density of the atmosphere through which the ram accelerator projectile travels offsets its smaller scale and lower Mach numbers, resulting in nearly equal Reynolds numbers. The range of Damkohler parameter (ratio of fluid dynamic timescale to chemical reaction timescale) is also roughly the same for these two devices. It is extremely difficult for other ground-based test facilities, for example, shock tunnels, to obtain exact similitude of Mach number and Reynolds number. The only aspect of scramjet propulsion missing from the ram accelerator is fuel–air mixing, but often it is desirable to eliminate mixing from studies to isolate combustion and propulsive performance issues under idealized conditions. Some hypersonic airbreathing concepts, such as the shock-induced combustion ramjet,[10] involve injecting fuel into the air far upstream of the combustor, that is, in the inlet, so that effectively premixed fuel and air enters the combustor, in which case the correspondence with the ram accelerator becomes nearly exact.

Since the concept was proposed and first demonstrated experimentally at the University of Washington in the 1980s by Hertzberg et al.,[1] other ram accelerator facilities have become operational elsewhere in the United States, as well as in France, Germany, and Japan. Velocities of 2700 m/s have been achieved, and projectiles as massive as 5 kg (in a 120-mm-bore launch tube[11]) have been successfully accelerated. Unique facilities, such as a two-dimensional ram accelerator with a wedge-shaped projectile to facilitate flow visualization,[12] have also been successfully operated. A number of computational studies of ram accelerators have been done over the past 20 years, as well as experiments and simulations examining the interaction of supersonic projectiles with detonable gases and other related phenomena.

For a comprehensive review of ram accelerator developments to date, the interested reader is encouraged to consult Refs. 13 and 14. The detonation-related aspects of the ram accelerator were recently reviewed by Nettleton.[15] Rather than a comprehensive review, this paper has a somewhat different aim. The focus of the first half is to highlight the unresolved, or outstanding, issues that must be addressed for the ram accelerator to realize its full potential. The second half of the paper explores novel directions that the ram accelerator concept could take that offer the potential for a dramatic increase in projectile acceleration and maximum velocity.

II. Subdetonative Operation

To date, the emphasis of ram accelerator research has been on subdetonative operation, in which the projectile travels at velocities less than the Chapman–Jouguet (CJ) velocity of the gaseous propellant mixture. The combustion process in this regime typically occurs in a zone of subsonic flow relative to the projectile, downstream of a normal shock or shock-train system stabilized on the projectile, as shown in Fig. 1a. At Mach numbers less than the CJ Mach number, isentropic compression and oblique shock waves cannot increase the temperature of combustible mixture sufficiently to initiate combustion in the supersonic portions of the flow. Combustion in the subdetonative regime is typically stabilized behind the blunt base of the projectile, which is believed to play the role of a flame holder. The heat release of combustion is sufficient to choke the flow in the full tube area behind the projectile. This choked condition stabilizes the shock system on the projectile and isolates the flowfield around the projectile from the unsteady expansion that occurs behind the projectile. The choking condition is analogous to the sonic plane of a CJ detonation.

The thermally choked, subdetonative mode produces somewhat greater thrust than the superdetonative mode (Fig. 1b, discussed further in Sec. III) for the same propellant mixture and also limits the aerodynamic heating of the projectile because in-tube Mach numbers are maintained below Mach 5. Note that this is not the only possible mode of operation with subsonic combustion.[1] For example, a projectile with a second throat after the combustion zone can mechanically choke the flow, followed by a nozzle section to expand the flow supersonically (as in a conventional ramjet). This mechanically choked mode has a greater thrust potential and higher maximum velocity than the thermally choked mode.[1] To date, no experimental investigation of this other mode has been conducted, and the requirement to stabilize combustion in the region between the inlet throat and the nozzle throat may prove problematic. The remainder of this section instead examines the classical thermally choked mode in greater detail.

A. Model of Operation

The thermally choked ram accelerator can be effectively modeled using a control volume or black box analysis. The model here assumes that the propellant mixture is calorically perfect, with the effect of combustion modeled as an external heat addition. One-dimensional models of varying sophistication can include the effects of variable heat capacity, chemical equilibrium, flow unsteadiness, and nonideal gas equation of state (required for initial pressures exceeding 50 atm).[16–18] The qualitative trends discussed hereafter, however, are the same for these different levels of modeling.

For a control volume enclosing the projectile in a steady, projectile-fixed reference frame, the conservation laws of mass, momentum, and energy are

$$\rho_1 u_1 A_1 = \rho_6 u_6 A_6 \tag{1}$$

$$F = \left(p_6 + \rho_6 u_6^2\right) A_6 - \left(p_1 + \rho_1 u_1^2\right) A_1 \tag{2}$$

$$h_1 + u_1^2/2 + \Delta q = h_6 + u_6^2/2 \tag{3}$$

The subscript 1 refers to the supersonic flow entering the projectile control volume, and subscript 6 refers to the flow exiting the control volume. Here, Δq is the heat release resulting from combustion, which is treated as heat addition from an external source into a calorically perfect working fluid. The heat release of combustion is nondimensionalized by the temperature and heat capacity of the

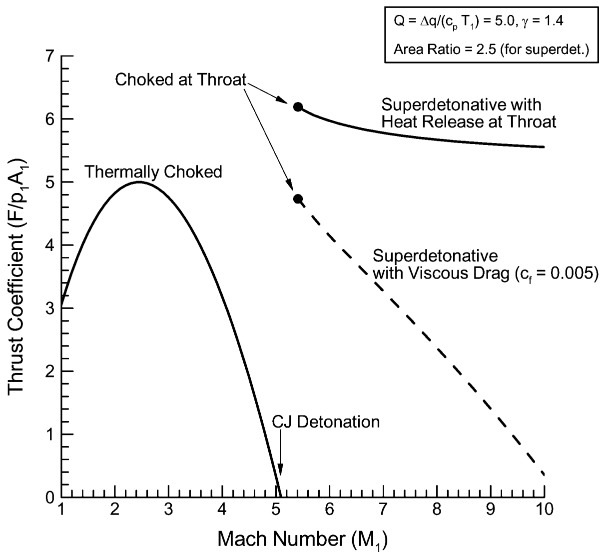

Fig. 2 Thrust on ram accelerator projectile (normalized by fill pressure and tube area) for thermally choked and superdetonative modes of operation.

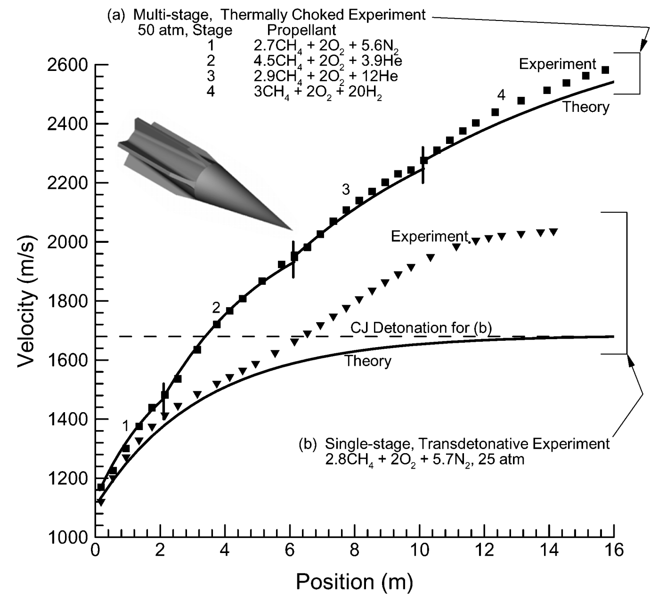

Fig. 3 Experimental velocity-position data from 38-mm University of Washington ram accelerator using 70-*g* projectile (shown) for a) multi-stage, thermally choked operation and b) single-stage, transdetonative operation.

initial mixture,

$$Q = \Delta q / c_p T_1 \tag{4}$$

When it is assumed that the flow exits the control volume at sonic velocity relative to the projectile ($M_6 = 1$), the thrust on the projectile can be solved for

$$F/p_1 A = M_1 \sqrt{2(\gamma+1)\left\{1 + [(\gamma-1)/2]M_1^2 + Q\right\}} - \left(1 + \gamma M_1^2\right) \tag{5}$$

The assumption that the flow is thermally choked as it leaves the projectile control volume is analogous to the CJ condition for detonations, that is, a sonic plane is necessary to match the steady (or quasi-steady) flow around the projectile with the unsteady expansion of combustion products downstream.

Equation (5) is shown in Fig. 2 for a value of $Q = 5$, which is representative of the heat release of mixtures typically used in ram accelerators. Note that the thrust curve has a peak at Mach 2.5; this point can been shown to correspond to the condition where the propellant leaves the control volume at rest with respect to the fixed tube.[1] The thrust goes to zero at Mach 5.1. This condition can be determined from Eq. (5) by setting thrust equal to zero and solving for the heat release Q:

$$Q = Q_{\max} = \left(M_1^2 - 1\right)^2 / 2(\gamma+1)M_1^2 \tag{6}$$

Note that this is the value of heat release required to choke a constant area flow initially at Mach number M_1, which is the maximum amount of heat that can be added to a steady flow. Solving this for Mach number

$$M_{\max} = M_{\mathrm{CJ}} = \sqrt{(\gamma+1)Q + 1 + \sqrt{[(\gamma+1)Q+1]^2 - 1}} \tag{7}$$

This can be recognized as the CJ Mach number for a detonation with heat release Q. [Note that there is another solution to Eq. (6) that corresponds to a CJ deflagration.] Thus, the maximum velocity obtainable with the thermally choked ram accelerator corresponds to the CJ detonation velocity of the mixture.

The use of the steady form of the conservation laws may raise concerns because the projectile is accelerating and the resulting flowfield is unsteady. The acceleration and flowfield unsteadiness, however, must be compared to the characteristic timescale of the flowfield to determine if these effects are significant. For example, a fluid particle requires about 100 μs to traverse the control volume surrounding the projectile, during which time the projectile velocity will only change on the order of a few percent for typical values of acceleration (30,000 g) and velocity (1000–2500 m/s). Thus, the flowfield can justifiably be treated, to the first order, as quasi-steady.[19] When the projectile acceleration becomes very large, for example, when initial fill pressure exceeds 100 atm, the acceleration and unsteady effects are no longer negligible and must be included. This case was treated by Bundy et al.[20] and Bauer et al.[21] who constructed an analytic model for thrust including unsteady and acceleration effects. They showed that when accelerations exceed 100,000 g, the peak thrust can decrease by as much as 25% from the value predicted by Eq. (7) due to unsteady effects. Interestingly, they also found that this effect is offset by real gas effects encountered at higher initial fill pressures, which increase thrust from the value predicted by the ideal gas equation of state.

A comparison of the one-dimensional, control-volume model for the thermally choked mode with experimental results obtained from the University of Washington 38-mm-bore ram accelerator is shown in Fig. 3a. [Note that a chemical equilibrium computer program was used to solve the conservation equations (1–3) for thrust, subject to the condition of sonic outflow, rather than applying Eq. (5) directly.] The projectile was tracked as it accelerated down the launch tube by tube-mounted electromagnetic probes that detected the passage of a magnet carried onboard the projectile. The agreement is seen to be good, and overall the use of the thermally choked model has proven to be sufficient to predict projectile acceleration for velocities up to about 90% of the CJ velocity. (Deviation from the model is seen in single-stage experiments such as that shown in Fig. 3b and is discussed in Sec. III.) Note that, in the experiment shown in Fig. 3a, four different propellant mixtures were used to maintain high thrust by keeping the in-tube Mach number in the range of from Mach 3 to 4.5 as the projectile accelerated. This was accomplished by varying the acoustic speed of the propellant gases. The 70-g aluminum projectile was seen to accelerate from 1100 to 2700 m/s in 16 m of travel, corresponding to an average acceleration of 19,000 g.

Note that neither the shape of the projectile nor the details of the flowfield around the projectile affect the thrust predicted by the one-dimensional control volume model.[22] This counterintuitive result is a consequence of the assumption of thermal choking: Once the thermodynamic state at the exit of the control volume is specified, the thrust on the control volume is uniquely determined. This also implies that drag on the projectile or stagnation pressure losses do not influence thrust. Although projectile drag and pressure losses resulting from shock waves may alter the flowfield, as long as the flow remains choked downstream of the projectile, the flowfield will be altered in such a way as to maintain the same net thrust on the projectile as dictated by Eq. (5). Although the details of the flowfield around the projectile do not affect thrust, they can influence the ability to stabilize the combustion wave, permitting quasi-steady operation. For example, a significant enough disturbance to the flow, such as a bow shock on the blunt leading edge of a fin, may result in gasdynamic unstart of the inlet, forcing a normal shock wave upstream of the projectile and terminating positive thrust; in this instance, Eq. (5) would no longer apply.

The good agreement between predicted and experimentally observed acceleration can be taken as validation of the assumption of thermal choking behind the projectile. Alternatively, it is possible to relax the condition of thermal choking and instead use the experimentally measured accelerations [along with the conservation laws, Eqs. (1–3)] to determine what the state of flow exiting a steady control volume attached to the projectile must be. Such a calculation was performed by Knowlen and Bruckner,[23] and, from experimentally observed accelerations, the equilibrium flow exiting a steady control volume around the projectile was shown to be within 20% of the sonic velocity for projectile velocities below 90% of the CJ velocity. Experimental measurements of the pressure downstream of the projectile, made via pressure transducers mounted on the tube wall, have also been compared to the pressure predicted by thermal choking theory, and the agreement has been found to be within 10% (Ref. 24). Thus, the basis for the key assumption of the thermally choked model appears to be sound.

B. Challenges

Whereas results with the thermally choked model demonstrate good agreement with experiment and validate the potential of the ram accelerator as a hypervelocity launcher, there exist several challenges to implementing the concept. One is the initiation and stabilization of combustion on the projectile. At Mach numbers below approximately four, the isentropic compression and oblique shocks of the flowfield around the projectile are insufficient to initiate chemical reaction. The usual practice to initiate operation is to inject the projectile into the first propellant stage with a disk that blocks the full tube area behind the projectile. Such a disk, or obturator, is typically required in the prelauncher anyway because the ram accelerator projectile is subcaliber. When this obturator impacts the first stage of propellant mixture, it drives a strong normal shock up onto the projectile in front of it and initiates combustion. The details of this process are complex and highly unsteady, and the residual gases in the evacuated prelaunch tube (which undergo an enormous adiabatic compression as the projectile/obturator travel down the prelaunch tube) are also believed to play a critical role in igniting the first stage of propellant.[25–27] Although initiating stable operation is an important technique, it does not have direct bearing on the overall realization of the ram accelerator concept. In fact, it has been demonstrated that thermally choked operation can also be initiated via an active igniter onboard the projectile[28] and can even be initiated without the presence of an obturator at all.[29,30] Thus, the starting process will not be elaborated on further, and instead the focus will be on the issues that control the accelerations and the maximum velocities that can be achieved using the ram accelerator.

1. Limits to Operation

In the experimental results shown in Fig. 3a, note that all of the propellant mixtures used were formulated fuel rich, for example, fuel equivalence ratios from 2.7 to 4.5, and with a large concentration of inert gas (nitrogen, helium). Much greater projectile acceleration would have been obtained if more energetic, that is, less dilute, mixtures could have been used. The use of significantly more energetic mixtures than those shown in Fig. 3, however, will result in the combustion wave surging past the projectile and unstarting the diffuser. The unstart results in a very strong normal shock being driven down the tube in front of the projectile, and rapid deceleration (and often destruction) of the projectile. The term unstart derives from the supersonic inlet literature and refers to the disgorging of a normal shock wave from an inlet and the cessation of supersonic flow through the inlet throat.

The range of stable operation of the ram accelerator has been experimentally mapped in two classes of propellant mixtures.[29,30]

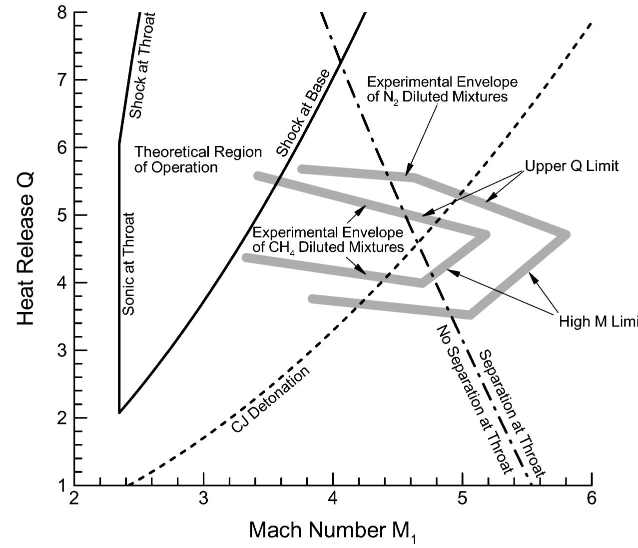

Fig. 4 Experimentally measured and theoretically computed envelopes of operation.

The envelope of successful operation defined by these experiments is shown as a function of the projectile Mach number M and the heat release Q of the mixture in Fig. 4. Note that in all of these experiments, the projectile initially entered a reliable first-stage starting mixture, such that stable operation could be initiated for the first 2–4 m of projectile travel, before transitioning to mixtures with variable amounts of dilution. At values of heat release greater than the upper boundary of the envelope shown in Fig. 4, an immediate unstart was observed. At values of heat release below the lower boundary of the envelope, combustion was quenched and the projectile coasted down the tube, decelerating due to aerodynamic drag. Projectiles that successfully accelerated either exited the test section or eventually unstarted, forming the right boundary of the envelope of operation in Fig. 4. The high Mach number limit is believed to be influenced by both gasdynamics and the projectile's structural integrity. Indeed, the boundary of the envelope in Fig. 4 at high Mach number ($M > 5$) was shown to be dependent on the projectile material (magnesium vs aluminum vs titanium).[30] Note that the high Mach number boundary actually exceeds the CJ Mach number of the propellant mixture, where the thermally choked model predicts thrust ceases; this is due to the ability of the projectile to continue to accelerate in the transdetonative velocity regime, as discussed further in Sec. III.

The salient result of Fig. 4 is that the ram accelerator appears to be limited to mixtures with values of heat release $Q < 6$ by an upper Q limit. Because the thrust on the projectile scales directly with the heat release, as shown by Eq. (5), this restriction on the mixture heat release limits the accelerations that are obtainable for a given propellant fill pressure. For example, if propellants of a nearly stoichiometric undiluted combustible mixture, for example, $1.5CH_4 + 2O_2$, $3H_2 + O_2$ with values of $Q \approx 15$, could have been used at the same initial fill pressure as the experiment shown in Fig. 3, then the projectile would have reached a velocity of 3000 m/s in one-half the distance of travel (8 m, rather than 16 m) and would have exhibited an increase in average acceleration by a factor of more than two. Clearly, it is worthwhile to further investigate what is responsible for the unstarts that impose the upper Q limit on the envelope of operation.

A number of experiments were performed to scrutinize the upper Q limit in Fig. 4 (Ref. 30). A particularly intriguing result was that, if the combustion wave was stripped from the projectile by first passing it through a stage of inert gas, for example, nitrogen, the projectile was able to supersonically coast through mixtures that were too energetic to permit stable ram accelerator operation. In some instances, a combustion wave was observed to reinitiate in the wake of the projectile, catch back up, and briefly reestablish ram accelerator operation before surging past the projectile and unstarting

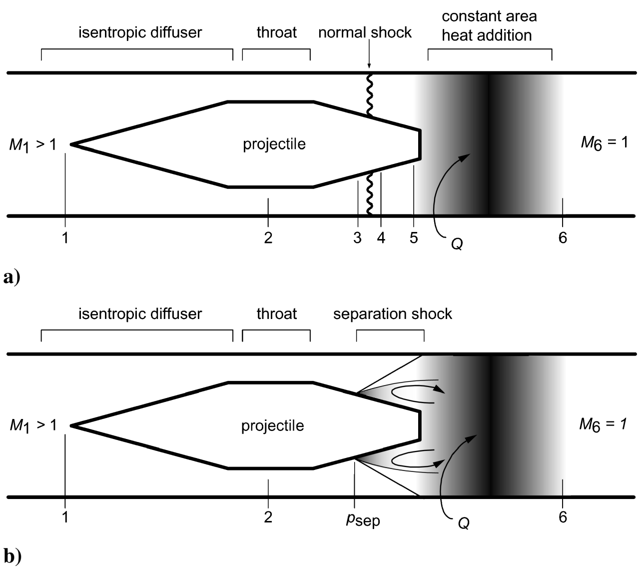

Fig. 5 Models of operation in thermally choked mode: a) one-dimensional model with normal shock wave and b) separation-induced shock model.

the diffuser. These results clearly indicated that the limit on high Q operation is not shock-induced combustion or other phenomena occurring as the combustible mixture flows over the projectile throat, but rather is due to the inability of the driving combustion wave to be contained behind the projectile. If the mechanism responsible for driving the combustion wave past the throat (or, conversely, the mechanism responsible for containing the combustion wave behind the throat in the cases of successful operation) can be identified and controlled, then the possibility exists to operate in significantly more energetic mixtures.

The observed limits to operation are difficult to explain within the context of a one-dimensional model of the ram accelerator flowfield, as shown in Fig. 5a. If the combustion is assumed to occur in the constant-area tube behind the projectile and the flow over the projectile is isentropic except for a single, normal shock wave, then it is possible to use classic gasdynamic relations to compute a theoretical envelope of operation for which the normal shock wave is stabilized on the projectile tapered base. The theoretical limits are 1) a minimum Mach number to maintain supersonic flow past the throat, 2) a maximum value of heat release, beyond which the normal shock is pushed past the throat, and 3) a minimum value of heat release to keep the normal shock stabilized on the projectile. For isentropic flow over a projectile that tapers to a point, this third limit corresponds to the CJ condition. The theoretical envelope defined by these limits is shown in Fig. 4, and clearly it is not sufficient to predict the experimentally observed region of stable operation: The experimentally observed region of operation is seen to correspond to conditions where the normal shock should have fallen off the base of the projectile. Including stagnation pressure losses to account for realistic diffuser efficiencies, etc., shifts the theoretical envelope only slightly. Moreover, the model predicts that, as the projectile accelerates, the normal shock system should recede from the throat, making unstart less likely at higher velocities. It is clear that an essential detail is missing from this simple flowfield model because unstarts with accelerating projectiles have been observed. As the combustion stripping experiments discussed earlier proved, this missing detail is not combustion on the projectile forebody resulting in a premature choking of the flow.

One possibility is the initiation of a detonation wave in the propellant mixture in the wake, which would then overtake the subdetonative projectile. The detonation dynamic properties, for example, detonation cell size, critical diameter, etc., that could give a quantitative indication of the detonability of the propellant mixtures have not been adequately investigated, although the detonability limits of some ram accelerator mixtures have been studied by Bauer and Legendre.[31] The studies that have been done on the detonation characteristics of ram accelerator propellants have shown these compositions to be very difficult or impossible to initiate, particularly diluted, methane-rich mixtures.[32,33] The possibility of a deflagration to detonation (DDT) type event occurring in the combustion zone behind the projectile, however, cannot be ruled out. The current understanding of the DDT process is that a turbulent flame must undergo acceleration to the point where it is traveling at approximately one-half of the CJ velocity and drives compression waves of sufficient strength into the unreacted gas in front of it to autoignite the mixture via adiabatic compression.[34,35] It is unclear if these critical conditions for the onset of detonation can occur in the wake of the projectile that is already traveling at velocities greater than one-half CJ, particularly if the blunt base is acting as a flame holder. In other words, the gas may simply be burned out before it can reach the critical conditions required for the onset of detonation, similar to a pilot light that prevents an explosive concentration of gas from developing. Indeed, experiments in which a blunt projectile (sphere) is fired at supersonic speeds into a highly detonable mixture ($2H_2 + O_2 + 7Ar$) confined in a narrow tube have shown that DDT is possible in the wake of projectiles traveling faster then Mach 2, but the DDT process occurred many tube diameters downstream of the projectile.[36] At present, there is no quantitative theory of DDT, but available empirical correlations[37] suggest that DDT would not be possible if the propellant gas is burned within a few diameters of the projectile.

To make a definitive assessment of the relevance of DDT to the ram accelerator, it would be necessary to quantify the dynamic parameters of the propellant mixtures involved. Cell size measurements at elevated pressures are particularly difficult because the smoke foil technique is no longer practical due to the removal of soot from the foil by the detonation; measurements of critical diameter may be more feasible but have not yet been performed at high pressure. Also, the role of a preexisting, turbulent flow (such as that found in the wake of a supersonic projectile) on the DDT process has not be studied. This may be a profitable area of research because it has application to other propulsion concepts such as the pulse detonation engine.

2. *Role of Separation in Unstarts*

Another potential explanation of the limit on allowable levels of heat release in the propellant mixture is flow occlusion caused by boundary-layer separation. The idealized model of the flowfield discussed earlier (Fig. 5a) assumed the shock wave to be a single normal shock. It is well known that a shock wave stabilized in a duct is actually comprised of a series of normal and oblique shocks that form a shock train due to the presence of boundary layers on the duct wall.[38] It is likely that such a shock system is present on the projectile, and the length of the shock train means that it could be forced past the throat and into the diffuser, resulting in an unstart, under conditions where the idealized normal shock would not. This shock train may also explain why the stable region of operation corresponds to conditions where the normal shock wave would have fallen off of the projectile base (Fig. 4).

Shock trains in ducts have been widely studied,[39–41] and it is commonly accepted that the shock train will respond to changing upstream and downstream flow conditions in a qualitatively similar manner as a normal shock. For example, a decrease in backpressure will result in the shock train moving further downstream. In the case of the ram accelerator, however, this is not necessarily the case. As the projectile accelerates, the static pressure at the throat actually decreases (for the case of isentropic flow) or remains approximately constant. The post-combustion pressures, however, continuously increase. This is shown in Fig. 6, where the throat pressure and the pressure dictated by the condition of the thermal choking at the exit plane of the control volume are plotted, and an increasingly adverse pressure gradient can be seen as the projectile accelerates. This adverse pressure gradient may result in the shock system actually moving further upstream, toward the throat, as the projectile accelerates.

The separation of boundary layers in supersonic flows has been studied, for example, in overexpanded rocket nozzle flows. Early

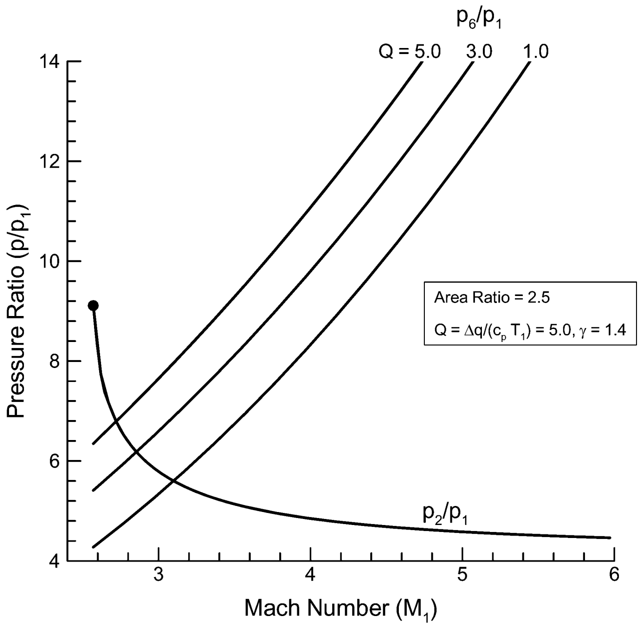

Fig. 6 Static pressure at projectile throat (p_2) and sonic choking plane (p_6) for different values of heat release as function of Mach number.

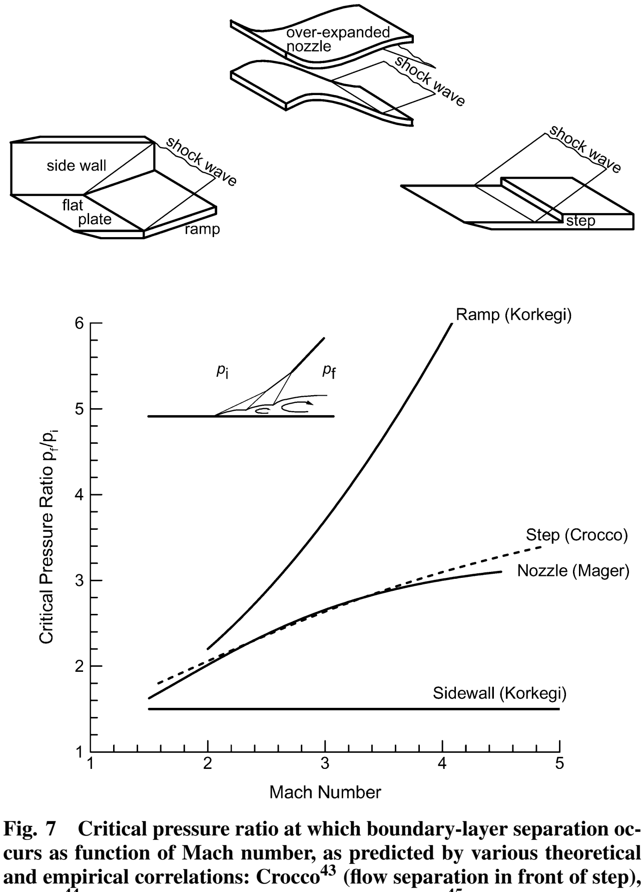

Fig. 7 Critical pressure ratio at which boundary-layer separation occurs as function of Mach number, as predicted by various theoretical and empirical correlations: Crocco[43] (flow separation in front of step), Mager[44] (free boundary separation), and Korkegi[45] (separation in front of wedge-supported shock).

experiments by Summerfield et al.[42] identified a critical ratio of downstream backpressure to the local pressure of approximately 2.5 as being the criterion for flow separation in nozzles. Figure 7 shows the results of models by Crocco[43] and Mager[44] and an empirical correlation by Korkegi[45] for the critical pressure ratio at which a separation shock appears in supersonic flow as a function of Mach number under different scenarios. The theoretical curves plotted are actually from semi-empirical models for separation that have been widely validated (and tuned) by experimental data; for clarity, the experimental data are not shown. The purpose here is not to provide a comprehensive review of boundary-layer separation in supersonic flows. Rather, Fig. 7 shows that although the adverse pressure gradient required for flow separation increases with increasing Mach number, the actual pressure gradient that the flow over the projectile experiences increases more rapidly, as seen in Fig. 6. This observation suggests that flow separation may become increasingly prominent as the projectile accelerates to higher Mach numbers.

Because the model by Mager[44] has been successful in predicting where free shock separation will eventually locate itself in an overexpanded nozzle flow in response to changes in the downstream backpressure, the model may be relevant in predicting where the separation shock will position itself on the ram accelerator projectile in response to the downstream pressure demanded by the thermal choking condition. This model is shown schematically in Fig. 5b. If we assume that the limit to operation will occur when the separation shock has been driven to the projectile throat and results in an unstart of the diffuser, it is possible to define a flow separation limit that can be compared to the experimentally determined envelopes in Fig. 4. It is seen that this separation limit does roughly match the trends of the upper Q limit that was experimentally observed. That this limit bounds a maximum Mach number is a reflection of the fact that the adverse pressure gradient becomes more severe as the projectile accelerates. The separation model used here is simplistic, and an alternative approach may be found by invoking models of shock trains or finite length pseudoshocks.[39–41] For example, by the use of existing correlations for the pressure distribution through shock trains in supersonic duct flows, it is possible to estimate the critical conditions at which the shock train is no longer able to be contained on the projectile, that is, shock train length equals throat-to-tail length. The results of this approach produce qualitatively similar results to the simple separation models presented here.

The influence of combustion on boundary-layer separation is neglected in all of these shock-separated flow models. Dramatic evidence supporting the possibility of combustion-induced boundary-layer separation forcing a shock system upstream is provided by the photographic study of a two-dimensional ram accelerator by Yatsufusa and Taki.[12] Taken with simultaneous shadowgraph and self-luminous photography, their photographs clearly show combustion in the boundary layer, forcing an oblique shock wave up the projectile body toward the throat as the projectile velocity increases. Other photographic studies[46] have shown combustion in the boundary layer beginning on the projectile forebody, making the resulting flow blockage even more significant. The description of the ram accelerator flowfield that is emerging suggests that further attention should be focused on the boundary-layer separation issue and may provide directions for future development that could overcome the limitation on mixture heat release. One possible remedy to the unstart problem via modifying the tube geometry is discussed in Sec. IV.A.

III. Superdetonative Operation

The thermally choked mode of operation is limited to velocities approximately equal to the CJ detonation velocity of the propellant mixture. Significantly higher velocities can be achieved by using a mode of propulsion that does not decelerate the flow to subsonic speeds relative to the projectile. When supersonic flow is maintained over the entire projectile, it is possible for the projectile to accelerate to velocities much greater than the CJ detonation speed. This superdetonative regime of operation is analogous to a scramjet, in which combustion occurs in a supersonic stream, as shown if Fig. 1b.

The mechanism of combustion in the superdetonative regime may be via an oblique detonation, shock-induced combustion occurring decoupled from the initiating shock wave, or a combination of the two. It is also likely that combustion will occur in the boundary layer as well. That the stagnation and postshock temperatures are sufficient to initiate reaction is the principal difference between the superdetonative and subdetonative regime.

The existence, structure, and stability of oblique detonation waves have received considerable attention in recent years, due in part to

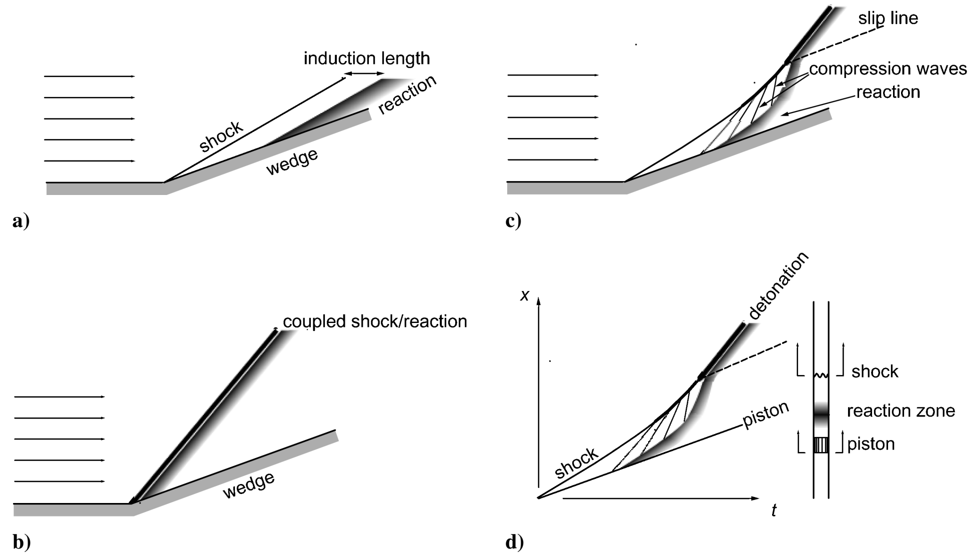

Fig. 8 Shock-induced supersonic combustion stabilized on wedge: a) shock-initiated combustion occurring at fixed distance downstream of oblique shock, b) oblique detonation with combustion coupled to shock, c) transition of shock-induced combustion to oblique detonation via compression waves generated by volumetric dilation of combustion products and d) analog to one-dimensional, piston-initiation detonation.

their relevance to the superdetonative ram accelerator. A comprehensive review of the geometry of oblique detonation waves permitted by the steady conservation laws was given by Pratt et al.[47] Experimentally, oblique detonation waves were first observed in a unique apparatus in which a high-velocity gaseous detonation wave was used to drive a virtual wedge into a bounding, gaseous mixture with a lower detonation velocity.[48] In these experiments, shock-induced combustion, oblique detonation waves, and the transition of shock-induced combustion to oblique detonation waves was observed, depending on the mixture sensitivities and pressures used in the experiments.

Perhaps the clearest evidence for the existence of oblique CJ detonations was provided by photography of large-scale field experiments by Radulescu et al.,[49,50] in which a linear charge of energy (detonating cord) was used to initiate a detonation wave in a combustible mixture of gases along a line with a very large phase velocity (6400 m/s, or Mach 18). The resulting conical detonation that propagated outward into the surrounding combustible atmosphere (C_2H_4/air) was observed to be in excellent agreement with the angle predicted by the oblique detonation analog to a Mach line: $\alpha = \sin^{-1}(u_{\mathrm{CJ}}/u_{\mathrm{source}})$. As the mixture was made less sensitive or the energy of linear source was decreased, the oblique detonation front became increasingly irregular and consisted of discrete, localized explosions, similar to patterns previously observed in the case of critical initiation of spherical detonations.[51] The envelope of the discrete explosions, however, still formed an oblique detonation front. The critical values of the energy of the linear source, and the mixture sensitivity at which the discrete detonation centers no longer formed an oblique front, agreed well with theoretical estimates of the critical energy required to initiate a cylindrical detonation.[49]

Despite the considerable interest in oblique detonation, whether oblique detonation (Fig. 8b) is desirable in comparison to shock-induced combustion (Fig. 8a) remains an open question. In particular, a sequence of weak oblique shock waves, for example, reflecting between a ram accelerator projectile and tube wall, can bring the combustible mixture to reaction with less total pressure loss than a single, steep oblique detonation. The oblique detonation may have an advantage over shock-induced combustion in that the detonation occurs earlier on the projectile and in a narrower region, permitting the combustor length to be short and thereby mitigating viscous drag losses. These same advantages apply to the oblique detonation wave engine in comparison to the conventional scramjet.

In practice, it is unlikely that the exact mode of combustion (oblique detonation vs shock-induced combustion) can be dictated. In fact, shock-induced combustion occurring at a fixed distance downstream of an oblique shock (Fig. 8a) is not a permitted solution of the steady conservation laws, unless it is in a CJ detonation or an overdriven detonation. Shock-induced combustion occurring with an oblique shock wave weaker than an oblique CJ detonation is not permitted, in the same way and for the same reasons that sub-CJ planar detonation waves are not permitted by the governing conservation laws. If a weaker shock wave does initiate reaction, the energy release of the reaction will eventually feed back into the oblique shock via compression waves, forcing it to steepen or kink into an oblique detonation. This scenario is shown in Fig. 8c. Such patterns have been observed experimentally and computationally.[52,53] In fact, this flow pattern is simply the two-dimensional, steady analog of the one-dimensional, unsteady problem of a piston forcing a shock into a reactive mixture: The wedge in a two-dimensional steady flow is analogous to an impulsively started piston in a one-dimensional, unsteady flow, as illustrated in Figs. 8c and 8d. The analog between these two phenomena was pointed out by Ghorbanian and Sterling[54] and elaborated on by Daimon and Matsuo.[55] Note that the flow pattern shown in Figs. 8c and 8d is scaled by the chemical induction time of the mixture. It may be possible that the kink to an oblique CJ detonation wave occurs beyond the flowfield region of interest. More likely, however, is that the reflected oblique shock propagating back into the induction zone will result in a prompt and coupled reaction, that is, oblique detonation will occur from the reflected shock before shock-induced combustion is complete from the incident oblique shock. Such a phenomenon was observed in computational simulations of the superdetonative ram accelerator by Li et al.,[56,57] in which an oblique detonation was seen to form after a series of oblique shock reflections. As the projectile accelerated in these simulations and the shock waves became stronger, the oblique detonation was observed to snap from a later shock reflection to an earlier oblique shock. This result suggests that the superdetonative ram accelerator should be able to maintain a combustion wave attached near the throat of the projectile over a wide range of projectile velocities.

Another point that has been raised in connection with the oblique detonation mode of the ram accelerator is the necessity of energy input (in the form of drag on the projectile) into the flow to initiate the detonation.[58–60] This model of oblique detonation initiation has been used to successfully predict the size and velocity required of a blunt projectile to initiate detonation in an unconfined combustible mixture.[36,58] This model has even been used to try to predict a limit on the velocities obtainable in a ram accelerator because the drag required to initiate detonation can be comparable to the thrust generated by the expansion of combustion products. Returning to Fig. 8, however, we can see that shock-induced combustion and oblique detonation are not necessarily directly initiated by drag when an oblique shock is reflected back and forth between the projectile and tube wall. In this sense (and again invoking the two-dimensional steady, one-dimensional unsteady analog), initiation of an oblique detonation in a supersonic flow is more akin to a DDT occurring in front of a piston in that the projectile or piston needs only to produce a shock sufficient to autoignite the mixture. The energy input (and, thus, drag) requirements are, therefore, substantially less. Thus far, this discussion has neglected viscous effects, which will likely render the picture more complex and may affect the stability of the oblique detonation and the overall operation of the superdetonative ram accelerator. The effect of viscosity on the structure of oblique detonation and shock-induced combustion has been examined by Yungster,[61] Li et al.,[62] and Choi et al.[63]

The existence of a mixed mode of propulsion in which combustion occurs partly on and partly behind the projectile in both supersonic and subsonic regions of flow, respectively, is strongly suggested by the ability of a projectile to accelerate from the subdetonative, thermally choked mode to superdetonative operation in a single mixture.[64] This result suggests that as the projectile approaches the CJ velocity of the mixture, combustion begins to occur in the supersonic flow past the projectile, likely due to shock-induced combustion or boundary-layer combustion. If a portion of the flow remains supersonic, the exit flow unchokes, and the projectile is able to continue to accelerate past the limitation imposed by Eq. (7). This phenomenon is often seen in experiments examining thermally choked operation: If the projectile is allowed to continue traveling in the same propellant mixture, an increase in acceleration is observed as the projectile approaches the CJ speed, permitting the projectile to continue to accelerate beyond the velocity limit imposed by the thermally choked model. This can be seen in the single-stage experimental result shown in Fig. 3b. The existence of this transdetonative regime suggests the possibility to transition from subdetonative to superdetonative within a single gas mixture, reducing the number of propellant stages involved. In applications of the ram accelerator, this transdetonative regime would probably be avoided because it has lower thrust than thermally choked or superdetonative operation, while at the same time it exposes the projectile to high Mach numbers and intense aerodynamic heating.

The transdetonative regime has been treated by a one-dimensional model in which the flow over the projectile following the normal shock is able to pass through the sonic condition and re-accelerate to supersonic by the combined effect of heat addition and area change.[65,66] In this case, a generalized choking condition is invoked to maintain continuous fluid properties, analogous to the generalized CJ condition for pathological detonations with competing source terms. This mode of operation is similar to the dual-mode scramjet operating in ramjet mode, in which the heat addition of combustion in a diverging duct permits subsonic flow to re-accelerate to supersonic without passing through a physical throat. Despite the utility of this model in providing a qualitative explanation the transdetonative phenomenon, the actual flowfield responsible for transdetonative operation is likely to be highly multidimensional, involving pockets of both subsonic and supersonic flow.

A. Model of Operation

A simple model of superdetonative ram accelerator operation is shown in Fig. 9. The flow is assumed to be isentropically compressed, and then the heat addition of combustion occurs in a constant-area annular section at the projectile throat; the mechanism of combustion (shock induced vs oblique detonation) is not specified. The flow then communicates thrust to the projectile as it expands back to the full tube area. The difference in momentum flux entering and leaving the control volume determines the thrust on the projectile. This thrust is shown in Fig. 2 for a value of $Q = 5$ and a ratio of tube area to flow-throat area of $\mathcal{A}\!\mathcal{R} = 2.5$.

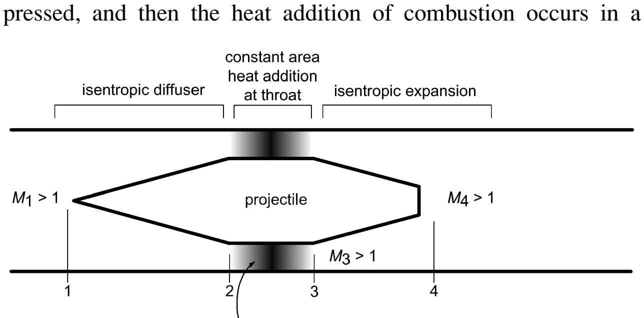

Fig. 9 Model of operation in superdetonative mode.

Note that it is now essential that details of the flowfield, such as the area contraction ratio and drag losses, be included. Unlike the thermally choked ram accelerator, where the flow leaving the black box control volume is a thermodynamically prescribed end state, the thrust generated by superdetonative model depends on the particular path the flow takes. For example, the higher the contraction ratio (greater compression), the greater the thrust generated will be for a fixed value of Q. Also, the influence of viscous drag (skin friction) becomes significant at hypersonic speeds, and this drag must now be included in the estimate of the thrust. The effect of skin drag can be qualitatively estimated using a constant skin-friction coefficient c_f,

$$F_{\text{drag}} = \int_{A_{\text{proj}}} \tau \, \mathrm{d}A_{\text{wet}} = \int_{A_{\text{proj}}} \frac{1}{2}\rho V^2 c_f \, \mathrm{d}A_{\text{wet}}$$

If a value of $c_f = 0.005$ is used as a pessimistic estimate of the skin-friction coefficient (for turbulent flow with $Re \approx 10^9$ on a smooth surface) and the ideal, one-dimensional flow solution is used to find density ρ and velocity V, the effect of viscous drag on the net thrust can be estimated, as shown in Fig. 2. Viscous drag is seen to reduce dramatically the predicted thrust as the projectile reaches hypersonic Mach numbers, until a thrust-equals-drag condition is reached at Mach 10–12. For this drag model, it is necessary to assume a geometric profile for the projectile: For these calculations, the projectile was assumed to be axisymmetric with a 10-deg half-angle for the nose cone and boat-tail base, with a constant-area section equal to one projectile diameter in length at the throat.

There has been comparatively little experimental work done on the superdetonative ram accelerator. This is partly because achieving superdetonative operation requires velocities on the order of 2000 m/s, which places considerable demands on the prelauncher or requires using thermally choked ram accelerator stages to bring the projectile to these velocities. The only facility dedicated to investigating this regime has been the 30-mm-caliber ram accelerator at French-German Research Institute Saint-Louis (ISL), which used an 1800-m/s-muzzle-velocity powder gun to inject the projectiles at superdetonative speeds into the ram accelerator tube. This facility was unique in that it used an axisymmetric projectile (no fins) that was centered in the tube by rails on the tube wall. The projectiles were observed to accelerate from 1800 m/s to velocities as great as 2050 m/s in the 4-m-long test section, using propellant mixtures of $2H_2 + O_2 + \chi CO_2$ at 20–45 atm initial pressure, with $\chi = 4$–8 (Refs. 67 and 68). Lower values of carbon dioxide dilution, $\chi = 3$, resulted in unstarts, presumably due to the thermal choking. (See discussion in Sec. III.B.1.) The maximum observed accelerations in these tests were on the order of 15,000 g. The observed projectile acceleration agreed well with a one-dimensional model of operation that was essentially the same as that presented here (Fig. 9). Tests were also performed with fin-guided projectiles in a modified version of the same facility using a smooth-bore ram accelerator tube.[69] The projectiles with fins were observed to accelerate only weakly or to coast at nearly constant velocity in a thrust-equals-drag condition. Similar studies of superdetonative ram accelerator operation with fin-guided projectiles at the University of Washington generated comparable results, and an analysis of the projectile drag suggested that drag on the blunt projectile fins is a substantial fraction of the total drag.[70] These results highlight the importance of projectile shape in superdetonative operation, in contrast to subdetonative thermally choked operation.

In all superdetonative tests done to date, the degradation of projectile integrity due to the intense aerodynamic heating encountered at high Mach number has been a poorly quantified factor in the experiment; this issue is address further in Sec. III. B. 2. Definitive tests of the superdetonative mode of operation will likely require using a two-stage light gas gun to bring the projectile to velocities well in excess of 2 km/s, such that a pristine projectile can be injected into the test section, ensuring that the phenomena observed are purely gasdynamic in nature and not influenced by the condition of the projectile. Tests along these lines were conducted by Sobota et al.[71] using projectiles launched from a 3-km/s light gas gun into a ram accelerator containing a hydrogen/air mixture; however, the details of the experimentally observed projectile accelerations from these tests were not published.

B. Challenges

1. Limits to Operation

The simple, one-dimensional model for performance discussed earlier can be used to predict the gasdynamic limits of superdetonative operation. If the heat release occurring in the annular region around the projectile is sufficient to choke the flow, it will unstart the diffuser. The pertinent relation for this case is Eq. (6), which is the maximum heat addition allowed in a steady flow. Note that now this relation applies by replacing M_1 with M_2, the flow at the entrance to the combustion area (not the full tube area). The critical value of $\Delta q/(c_p T_2)$ and M_2 can then be related to Q and M_1, knowing the contraction ratio of the inlet. This calculation defines a limit (for an area ratio $AR = 2.5$) that is plotted in the Q–M plane in Fig. 10; as with thermally choked operation, the Q–M plane is a convenient parameter space in which to represent the operating limits. The resulting envelope of choking suggests that once a projectile is traveling at greater than approximately 110% of the CJ detonation speed of the mixture, it should no longer be possible for the heat release of combustion to choke the flow. (Note that the exact velocity at which choking can no longer occur is a function of the area contraction ratio.) This means that the combustion-induced unstarts, which significantly limit the energetic content of mixtures used in the thermally choked ram accelerator, may no longer be a concern in the superdetonative ram accelerator. This conclusion has even led Seiler et al.[68] to suggest that the superdetonative mode may be preferable to the thermally choked mode because it could permit more energetic mixtures to be used.

To date, few experiments have been performed to determine conclusively the experimental envelope of superdetonative operation. Results from the ISL 30-mm-diam ram accelerator described earlier appear to support the one-dimensional model of Fig. 9. Mixtures with heat release values sufficient to choke the flow at the projectile throat, $\chi < 4$ for $2H_2 + O_2 + \chi CO_2$ mixtures, were observed to unstart promptly when the projectile was injected into the tube. Mixtures with values of heat release below the critical value, $\chi > 4$, successfully accelerated without unstart.

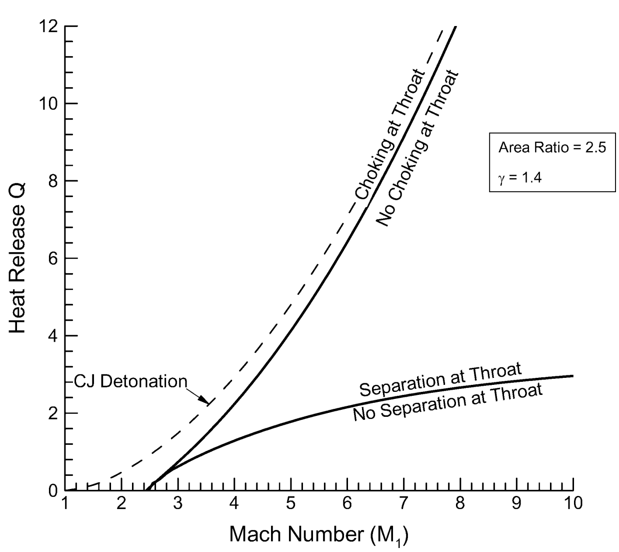

Fig. 10 Theoretically computed envelopes of operation for superdetonative ram accelerator.

That the supersonic combustion is accompanied by an increase in pressure in the streamwise direction again raises concerns about the influence of boundary layers and, in particular, boundary-layer separation. If we again apply the model of free boundary-layer separation that was described in Sec. II.B.2 to the model of superdetonative operation, it is possible to identify the region of the Q–M plane where the heat release of combustion results in a pressure gradient sufficient to cause flow separation. As seen in Fig. 10, the superdetonative ram accelerator would always be operating in a region of separated flow, except for the very low values of heat release, $Q < 2$.

The role combustion-induced separation may play in limiting the range of operation of the superdetonative ram accelerator has been investigated computationally by Choi et al.[72] These studies are particularly noteworthy in that they have examined the mechanisms that may be responsible for limiting the operational envelop of the ram accelerator, rather than focus on predicting ram accelerator performance. Their simulations show that unstarts in the superdetonative regime are associated with a separation bubble that develops at the projectile throat and is able to migrate upstream via the boundary layer, forcing a shock wave into the inlet and subsequent unstart. This sequence of events is illustrated by visualizations of their computations, shown in Fig. 11. Choi et al. also point out the important role that volumetric dilation of the combustion products have on the flow occlusion of a separation bubble; this effect is not included in the simple separation models discussed in Sec. II.B.2.

The role of combustion-induced separation resulting in diffuser unstart is well recognized in the scramjet literature. To prevent this effect in scramjets, an isolator, that is, a long, constant-area section, is introduced between the inlet and the fuel-injection/combustor section, to prevent combustion-induced separation from entering the diffuser. In a sense, the isolator acts as a rubber geometry section, allowing the flow to accommodate the strong adverse pressure gradient of the combustor without unstarting the inlet.[73] The ram accelerator, which operates with premixed fuel oxidizer, cannot use this remedy because the isolator would likely become the combustor. The same concern applies to the shock-induced combustion and oblique detonation wave engine concepts. In these devices, it is likely that alternative approaches to address the flow separation problem would need to be invoked, such as contouring the area profile of the projectile to relieve flow blockage caused by separation.

2. Material Effects

The focus of this paper is on the gasdynamic and combustion aspects of the ram accelerator. There are a number of other issues that will not be addressed involving the material and structure of the projectile and how well it survives the acceleration environment. A number of these issues, such as material gouging between the projectile and the launch tube walls, are not unique to the ram accelerator and occur in other hypervelocity launchers as well. The aerodynamic heating of the projectile is an important issue as well and has received considerable attention in ram accelerator research because structural weakening of the projectile and ablation of the projectile surfaces are believed to be major factors in limiting the maximum velocities that can be obtained in current facilities. The aerodynamic heating experienced by the ram accelerator projectile is particularly intense due to the high initial fill pressures used (typically 20–200 atm), but the heating issue is not qualitatively different than that experienced by hypervelocity projectiles and missiles traveling though the atmosphere. Thus, it will not be elaborated on here.

An issue that cannot be overlooked in connection with the gasdynamics of the ram accelerator is a reactive interaction between the projectile material and the gaseous medium through which the projectile travels: Material effects and, in particular, material combustion may have significant influence on the flowfield around the projectile. Striking evidence of material influence on the flowfield comes from the superdetonative 30-mm-diam ram accelerator at ISL. In experiments examining superdetonative operation (already discussed in Sec. III.A), it was observed that steel projectiles did not accelerate, the conclusion being that the mixture could not be

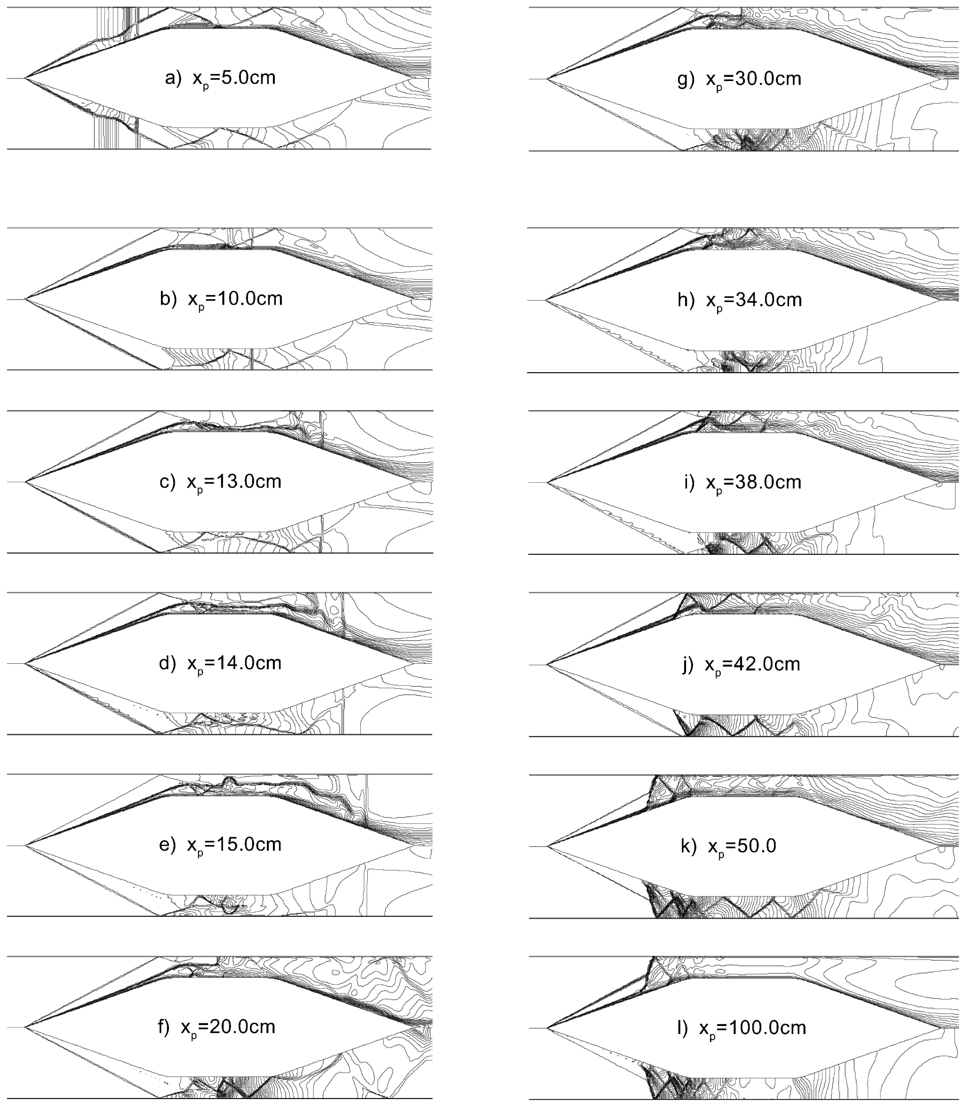

Fig. 11 Navier–Stokes simulation of superdetonative ram accelerator by Choi et al.[72] showing role of separation at projectile throat in unstart. Contours of temperature (upper-half) and pressure (lower-half) of flowfield are shown. Projectile injected at 2500 m/s into $2H_2 + O_2 + 5N_2$.

ignited by the adiabatic compression of shock waves alone.[68] Only projectiles with aluminum or titanium surfaces in the constant-area section of the projectile ignited the gaseous propellant and accelerated in the ram accelerator section. Clearly, the projectile material can have a significant influence on the flowfield. This result also raises the possibility that projectile burning may contribute energetically to the flowfield and result in additional projectile thrust. Seiler et al. concluded that, whereas the surface material may play a role in ignition, it does not contribute to the thrust and acceleration of the projectile because the metal combustion occurs on the back of the projectile.[68]

Evidence of projectile burning contributing to projectile acceleration has been observed in the 90-mm-diam ram accelerator facility at ISL.[74] This facility has focused mainly on thermally choked operation, but many successful experiments have resulted in projectiles accelerating through the transdetonative regime and exiting the ram accelerator at velocities approaching 130% of the CJ velocity of the propellant mixture. In these cases, a significant difference between aluminum and magnesium projectiles has been observed: The average thrust measured in experiments with magnesium projectiles was as much as twice that recorded with aluminum projectiles. This result was attributed to material combustion contributing to the heat released into the flowfield. Note that, in contrast to superdetonative operation, projectile material combustion downstream of the projectile could still contribute to thrust in subdetonative and transdetonative operation. An alternative explanation is that the reacting projectile surface may act as a flame holder, permitting combustion of the propellant gas to occur earlier on the projectile, thereby increasing thrust. Early experiments[75] in the transdetonative regime at the University of Washington also showed a significant influence on projectile material on acceleration in the transdetonative acceleration: Projectiles with nonreactive coatings could suppress transdetonative acceleration altogether and coast in a thrust-equals-drag condition at the CJ velocity, as predicted by Eq. (7).

Both the 30-mm and 90-mm facilities at ISL utilized flash x-ray photography to observe the condition of the projectile as it exited the ram accelerator. In both facilities, a large amount of mass removal has been observed from the projectile. Magnesium projectiles exiting the 90-mm ram accelerator after transdetonative operation were observed to have as much as 130 g of mass missing from the projectile (approximately 10% of the total projectile mass), mainly from the projectile fins.[74] Projectiles exiting superdetonative operation in the ISL 30-mm ram accelerator have also been observed to experience a large loss of projectile material, which, in the case of aluminum projectiles, has included almost the entire back half of the projectile.[67–69] Because the mass of projectile consumed is comparable to the mass of gaseous fuel in the propellant mixture, and because the energetics of metal and hydrocarbon combustion are similar, the contribution of projectile burning to thrust cannot be discounted. Recent efforts with the ISL 90-mm ram accelerator have sought to exploit this effect to increase acceleration by using a semicombustible projectile where a section of magnesium was located at the base of the projectile.[74] Veyssiere et al.[76] have suggested intentionally adding magnesium particles to the ram accelerator flowfield, either from the projectile itself or injected with the propellant mixture. The resulting accelerations and maximum velocities, however, are only predicted to increase by 10–20% with this technique.

The phenomenon of bulk metal combustion in high-speed flows of an oxidizing atmosphere has not been previously studied. This regime of combustion is distinct from the more familiar type of powdered metal combustion, as encountered in solid rockets and dust explosions, where the particle is at a uniform temperature as it burns. With a bulk metal, the majority of the metal remains cold, and exothermic reaction occurs only on the surface. The relevant nondimensional parameter is the Biot number (ratio of convective heat transfer at surface to internal heat conduction). All ram accelerator projectiles operate in the regime of large Biot number, meaning that heat transfer at the surface (either from aerodynamic heating or surface reaction) dominates over temperature conduction inside the projectile.

The ability of a bulk metal to burn in a supersonic flow in the large Biot number regime was demonstrated by Higgins et al.[77] using 1.3-cm-diam spheres of reactive metal (aluminum, magnesium, and zirconium) launched by a gas gun into oxidizing atmospheres (air, oxygen at elevated pressure). Minimum Mach numbers of five and four were found to be necessary to observe projectile combustion in pure oxygen environments with magnesium and aluminum projectiles, respectively. A more recent experimental investigation of this phenomenon by Tanguay et al.[78] has used a high-explosive-driven shock tube to accelerate flows of oxygen over stationary cylindrical samples of reactive metal. This technique permitted direct photography of the material samples in the supersonic flow induced by the passage of the shock wave. Intense luminosity on the projectile material was observed at shock Mach numbers over a range of 5–9, and the samples were recovered and measured for mass loss. No mass loss was observed in control experiments with inert gas (nitrogen), suggesting that the dominate mechanism of mass loss is surface reaction, rather than aerodynamic-heating-driven ablation alone. Remarkably, titanium and zirconium, which are often considered refractory metals, showed both combustion activity at lower shock Mach numbers and significantly greater mass loss than aluminum or magnesium samples. This result suggests that titanium, which has been increasingly used in ram accelerator experiments in recent years and has displayed improved survivability in superdetonative operation in comparison to aluminum, may, in fact, not be a suitable material for high Mach number ram accelerator operation.

The use of magnesium, aluminum, and titanium (all known to be reactive metals) for ram accelerator projectiles has been motivated by their high strength-to-mass ratio and ease of machining. Experiments with projectile coatings, including ZrO_2 and Al_2O_3, have shown some promise in their ability to protect the projectile,[69] but these coatings have not been investigated systematically. An issue that needs to be addressed is the ability of the coating to adhere to the projectile (which will typically have a different coefficient of thermal expansion) under extreme impulsive loading and thermal shock. To date, the use of advanced materials for projectiles has not been explored. For example, the existence of new ultrahigh-temperature ceramics, for example, ZrB_2, is creating interest in developing reentry vehicles with sharp leading edges.[79–81] Realization of this potential could have important application to ram accelerator projectile design. It is likely that other significant advances in materials will be made in the coming years, independent of ram accelerator developments; however, these advances could have a considerable impact on the maximum achievable velocities of ram accelerators.

A gasdynamic technique to ameliorate the effect of aerodynamic heating greatly is to create a core of pure hydrogen gas down the center of the launch tube. This hydrogen core would bathe the projectile with a low-density, low-molecular-weight gas without significantly compromising the energetic content of the overall propellant mixture. In addition, ensuring that the projectile surface does not contact an oxidizer will prevent reaction of the projectile surface material. Bulman,[82] Bogdanoff,[83,84] and Bogdanoff and Higgins[85] discuss various techniques to create the hydrogen core. The use of a hydrogen core would allow the projectile to reach velocities of 8000 to 10,000 m/s before surface temperatures exceed the melting point of refractory metals. Lowering the density of the gas in contact with the projectile surface also decreases viscous drag and could, therefore, also increase the thrust and maximum velocities achievable.

IV. New Directions

The remainder of this paper is devoted to new concepts or directions that development of the ram accelerator may take. To date, these concepts have yet to be conclusively demonstrated, but their potential to increase acceleration or ultimate projectile velocity dramatically in ram accelerators is sufficient to warrant drawing attention to them.

A. Baffles

The main factor restricting the projectile accelerations that can be obtained in ram accelerators is the boundary on propellant energetics imposed by the upper Q limit discussed in Sec. II.B.1 (Fig. 4). As the combustion stripping experiments confirmed, this limit is a result of the combustion wave surging from behind the projectile and unstarting the diffuser. It appears that the ram accelerator projectile does not have difficulty swallowing the incoming flow, even in the case of a highly reactive, energetic propellant mixture. Thus, if it were possible to install a one-way valve at the projectile throat that permitted in incoming propellant to be compressed but did not permit the combustion wave to surge from behind the projectile past the throat, then it would be possible to operate the ram accelerator in significantly more energetic mixtures.

One possible technique to isolate the inlet flow from the combustion wave downstream of the projectile is to use a launch tube with baffles or obstacles on the tube wall. The operation of such a baffled tube ram accelerator is shown schematically in Fig. 12. As the projectile throat reaches the baffle, it forms a seal that prevents downstream influence from reaching the inlet flow, effectively

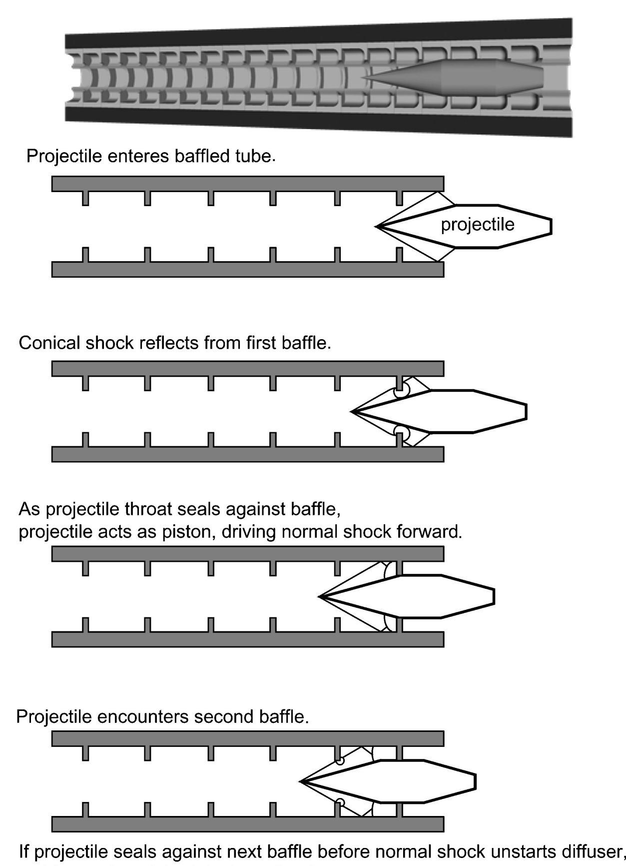

Fig. 12 Schematic of ram accelerator operation in baffled tube.

isolating the combustor section from the inlet. This one-way valve effect comes at the expense of considerably complicating the inlet flow: As the projectile approaches the baffle, interaction of the conical shock originating from the nose cone with the baffle will drive a normal shock into the gas ahead of the baffle. In the limit of a very thick baffle, this normal shock could be driven far enough ahead to unstart the inlet. Once the throat seals against the baffle, however, it no longer drives the normal shock, and the normal shock diffracts as it expands into the chamber defined by the baffle. If the baffles are spaced far enough apart, the inlet flow has time to recover and remain started before encountering the next baffle. Indeed, the inlet flow over the ram accelerator projectile has proven remarkably robust and is apparently not affected by passage through the plastic diaphragms that separate the various stages of propellant. (Note that, for high-fill pressure experiments, diaphragms can be as thick as several millimeters.) This suggests that the ram accelerator may be able to tolerate the perturbation to the flowfield created by the baffles.

If the constant-area section at the projectile throat is longer than the spacing between baffles, then the projectile is always sealed against at least one baffle, in principle making it impossible for a downstream event (such as the initiation of a detonation wave) to influence the inlet flow. This feature may permit a baffled tube ram accelerator to operate in a significantly more energetic propellant mixture. Other advantages of using a baffled tube may include operating with an increased tube area to increase the amount of propellant available. In traditional ram accelerators, increasing the tube area while the projectile size remains fixed makes stabilizing the combustion wave behind the projectile more difficult due to the increased potential for the combustion wave to surge past the throat. Finally, whereas the baffled tube is considerably more complex to fabricate, it permits much simpler and inexpensive axisymmetric projectiles to be used.

1. *Model of Operation*

The presence of baffles on the tube wall creates new possibilities of operating modes for the ram accelerator. One possible mode of operation is a variation on the thermally choked mode in which the flow exiting the control volume is still assumed to be thermally choked, but the net momentum flux acting on the control volume is assumed to act on both the projectile and the baffles. Because the flowfield around the ram accelerator usually results in gas motion down the tube in the direction of projectile motion (as viewed from the laboratory-fixed frame), the baffles result in a net drag on the control volume enclosing both the baffles and the projectile, resulting in lower thrust being communicated to the projectile. A subtle but important point is that, as viewed from a projectile-fixed reference frame, the baffles also do work on the flowfield around the projectile because they exert a force (drag) on the flow as they move through the control volume. This work term must be included into the energy equation (3) and has an effect similar to heat addition.[86] For most of the range of thermally choked operation, the net effect of the momentum losses and work addition caused by the baffles is to lower the net thrust and the maximum velocity that can be obtained. The exception is when the projectile is operating at Mach numbers less than the thrust maximum (typically, less than one-half of the CJ velocity). As discussed in Sec. II.A, at Mach numbers lower than the thrust maximum, the combustion products are moving in the direction opposite to projectile motion, as viewed from the laboratory-fixed frame. Thus, the presence of baffles results in a positive force acting on the control volume in this region of flow, which increases thrust. This effect is shown in Fig. 13, where the thrust coefficient with a baffled tube is compared to the classic thermally choked solution. Here, the baffles were assumed to be spaced one projectile diameter apart and have a drag coefficient of $C_D = 1$. This drag coefficient was then spread over the tube wetted area as an effective c_f. Note that the maximum velocity of the projectile is less than the CJ velocity due to the momentum losses to the baffles. This situation corresponds to the well-studied phenomenon of quasi-detonation, in which a detonation in an obstacle-laden channel propagates at steady, sub-CJ velocities due to momentum losses to the obstacles.[87,88] This model is only used to illustrate qualitatively the issues involved in thermally choked ram accelerator operation with baffles; the treatment of the flow over the baffles is too idealized to provide a quantitative prediction of the actual thrust.

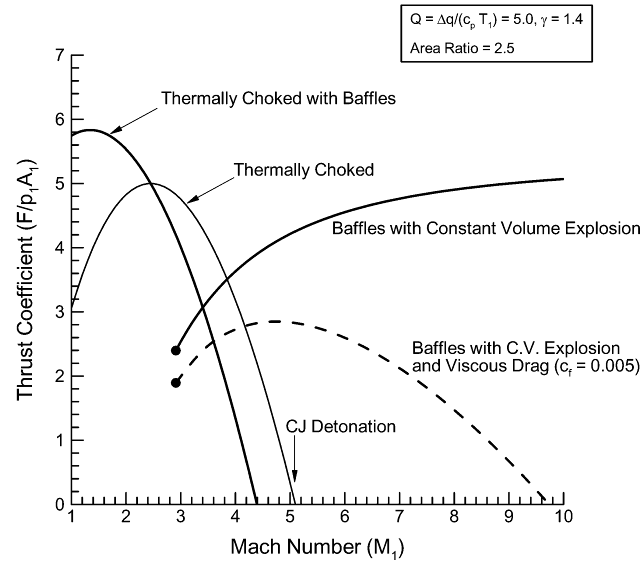

Fig. 13 Thrust on ram accelerator projectile (normalized by fill pressure and tube area) for possible modes of operation in baffled tube.

That the baffles define chambers of propellant as the projectile seals against them may permit entirely new modes of ram accelerator operation to be realized. If the propellant mixture contained in the baffle can undergo constant volume explosion in the time before the arrival of the tapered base of the projectile unseals the chamber, then the products of combustion can expand over the projectile base, generating thrust. In effect, this mode is similar to the superdetonative ram accelerator, only it utilizes constant volume combustion rather than constant cross-sectional area combustion in the annular region around the projectile throat. The thrust predicted by this mode is also shown in Fig. 13. In this model, the propellant gas is assumed to be isentropically compressed in each chamber in a laboratory-fixed reference frame, followed by the heat of combustion Q being added to the propellant as a constant volume explosion and the propellant then expanding isentropically over the projectile base in a projectile-fixed reference frame. The net thrust is computed by taking the difference between the drag and thrust on the nose cone and aft cone of the projectile, assuming one-dimensional isentropic flow over the nose cone and aft cone; the baffles themselves are assumed to have no influence on the flow or thrust. Note that without the presence of baffles, this mode of operation would not be possible at sub-CJ velocities because releasing the full heat of combustion at the projectile throat would result in thermal choking on the projectile and immediate unstart. Also note that this mode of operation is essentially identical to the distributed-injection launcher concept proposed by Gilreath et al.[89] (see Ref. 90), in which chambers of propellant are fired as a boat-tailed projectile passes each chamber. This mode of operation most likely defines the absolute limit of ideal performance that could be achieved with a baffled ram accelerator. Again, the intention here is not to make quantitative predictions of thrust in a baffled ram accelerator, but rather to underscore that novel modes of operation may be possible by modifying the tube geometry.

2. *Experimental Results*

Preliminary tests with a baffled ram accelerator tube at the University of Washington have shown that this technique permits the ram accelerator to operate, without unstart, in significantly more energetic mixtures than have previously been used.[91] Tests done in which a 38 mm diameter projectile was injected into a baffled tube with internal diameter of 64 mm and 3.2-mm-thick baffles spaced 28 mm apart. The baffled tube also featured rails, such than an axisymmetric projectile could be used without fins. A mixture of $2.7CH_4 + 2O_2$ was used without unstart (note that the standard mixture used in the thermally choked ram accelerator is $2.7CH_4 + 2O_2 + \chi N_2$, and values of nitrogen dilution less than 3.5 N_2 result in immediate unstart due to the "upper Q" limit discussed in Sec. II.B.1). The 1-m-long test section used in these experiments was too short to provide a conclusive measurement of projectile acceleration, but the recorded increases in velocity were less than the traditional thermally choked model would predict. It may be that the momentum losses to the baffles are significant and may offset the greater energetic content of the mixture. The design of the baffles may need to be modified in order to trade off their function in isolating the inlet from the combustion wave while minimizing their effect as a momentum loss. Another interesting aspect of these preliminary tests of the baffled tube concept was that no obturator was required, since the axisymmetric projectile was full-bore in the prelauncher and the mixtures used were sufficiently reactive to be ignited by the passage of the ram accelerator projectile.

B. Explosive-Lined Ram Accelerator

Condensed-phase explosives, that is, solid and liquid explosives, have volumetric energy densities three orders of magnitude greater than explosive mixtures of gases at standard temperature and pressure. This means that a ram accelerator utilizing a condensed-phase propellant has significantly greater energy available in the launch tube to accelerate the projectile than a conventional ram accelerator with gaseous propellant. In fact, to increase projectile accelerations, recent ram accelerator research at the University of Washington has used propellant initial pressures as great as 200 atm (Ref. 20), at which point the gaseous propellant begins to approach the volumetric energy density of high explosives. The disadvantage of the high-pressure approach is that the projectile must travel through this dense medium, which results in unacceptably high heat loads on the projectile. A ram accelerator invoking a solid explosive would use the explosive only on the tube walls; the projectile would travel down a tube filled with a low-molecular-weight gas, for example, hydrogen, for the reasons discussed in Sec. III.B.2. Thus, the projectile in a two-phase ram accelerator system would not be exposed to the hypervelocity flow of high-molecular-weight detonation products.

The potential for enormous accelerations and ultrahigh velocities in a ram accelerator invoking an explosive-lined launch tube was recognized in the original ram accelerator patent by Hertzberg et al.[92] A similar idea of using an explosive or propellant lining the walls of a launch tube was proposed by Rodenberger[93] and Rodenberger et al.[94,95] Other, closely related concepts, such as the blast wave accelerator, have also appeared in the literature in the recent years.[96–99] These concepts suffer from the necessity of having to synchronize the initiation of the explosive with the passage of the projectile. When a gasdynamic argument is used, it can be shown that releasing a propellant gas or explosive into the launch tube behind the projectile has no particular advantage over conventional, breech-fed guns.[90] Only if the propellant gas is released directly onto the tapered aft surface of the projectile does an explosive-lined accelerator have the potential to overcome the velocity limitations of conventional guns. An unusual, explosively lined gas cumulative accelerator was developed by Kryukov[99] in which a spinning, high-speed projectile would spray droplets of liquid metal onto an explosive sheet lining the launch tube, thus providing a mechanism to synchronize initiation of the explosive with the projectile. None of these concepts have been successfully implemented, and in all of these proposals the projectile would be exposed directly to the detonation products of the high explosive, which consist of high-molecular-weight compounds (N_2, CO, H_2O, etc.), resulting in unacceptably high heat loads on the projectile.

Explosives have been previously used to launch projectiles successfully to hypervelocities (in some cases, to velocities exceeding 12 km/s), however, these were one-shot, disposable devices that implode the launch tube itself behind the projectile to maintain a high driving pressure.[100] The potential advantage of the explosive-lined ram accelerator is that it could be operated as a reusable device by means of a thin coating of explosive inside a thick-walled, reusable

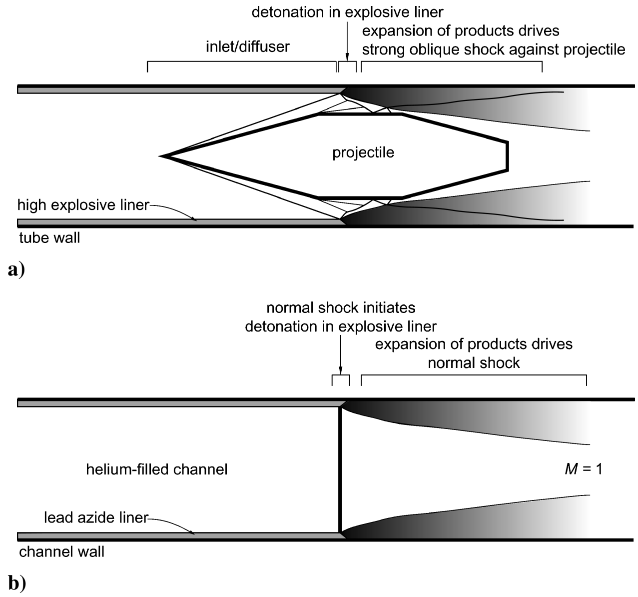

Fig. 14 Explosive-lined a) ram accelerator concept and b) channel experiment by Bakirov and Mitrofanov.[101]

launch tube. For example, a liner of explosive deposited on a disposable layer of foam could be inserted into the launch tube, so that the detonation of the explosive does not damage the launch tube itself.[85]

Although no definitive experiments have yet been conducted with the explosive-lined ram accelerator concept, an intriguing indication of the velocity potential of this concept is suggested in an experiment performed by Bakirov and Mitrofanov in the mid-1970s (Ref. 101). In their experiment, the inside surface of a 1-cm-diam channel was lined with a thin (0.1-mm) layer of a sensitive, primary explosive (lead azide), and the channel was then filled with helium. When a strong normal shock was transmitted into the channel, the shock initiated the explosive liner, and the shock wave was observed to accelerate to velocities of 14 km/s. This is a remarkable result, in that this velocity is nearly three times the CJ velocity of the homogenous lead azide. The interpretation provided by Bakirov and Mitrofanov[101] was that the normal shock in the helium initiated the lead azide explosive lining the tube, as shown in Fig. 14b. As the products of the explosive expanded into the tube, they constricted the flow downstream of the normal shock and, thus, drove the normal shock to a higher velocity, which in turn initiated the explosive faster. Thus, there existed a positive feedback coupling between the normal shock in the gas and the solid explosive lining, resulting in extremely high propagation velocities. A theoretical model developed by Mitrofanov[102] for detonation propagation in layered systems such as these showed that propagation velocities can be as great at 30 km/s. As discussed in the modeling of the thermally choked mode (Sec. II.A.1), the steady propagation velocity of a wave corresponds to a balance between the momentum flux and pressure acting on a control volume enclosing the wave. If the wave is forced to propagate at a lesser velocity by the inclusion of a projectile into the control volume, net thrust will be communicated to the projectile. Thus, by this argument, the arrangement shown in Fig. 14a should be capable of generating net thrust on the projectile to velocity of 14 km/s and possibly to much greater velocities.

1. *Model of Operation*

The performance of the explosive-lined ram accelerator was studied via computational simulations by Cambier and Bogdanoff.[103] For a 1-cm-diam aluminum projectile traveling at 10 km/s in a tube filled with 125 atm of hydrogen, a 1-mm-thick layer of explosive on the launch tube wall was predicted to be able to accelerate the projectile at 200,000 g. The maximum velocity potential of the device was not investigated in their simulations.

To estimate the maximum performance of explosive-lined ram accelerator, simulations have recently been performed using SolverII,

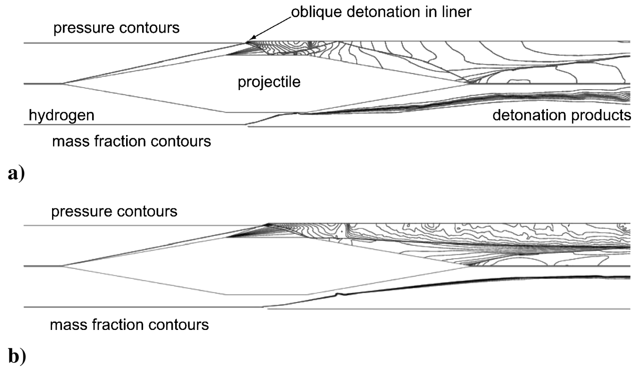

Fig. 15 Computational simulation of explosive line–ram accelerator showing pressure contours and mass fraction (hydrogen fill gas vs detonation products) at a) 12,000 m/s projectile velocity and b) 22,000 m/s projectile velocity.

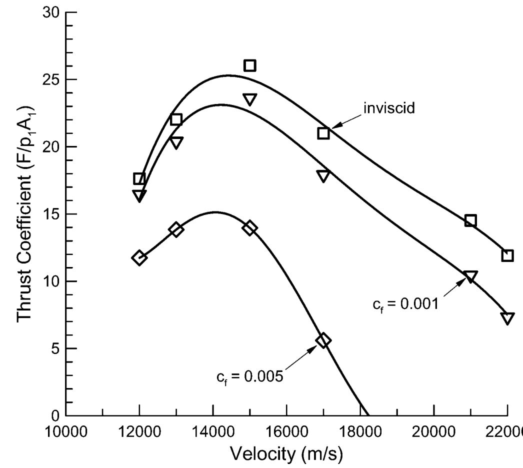

Fig. 16 Thrust on projectile in explosive-lined ram accelerator (normalized by hydrogen core fill pressure and tube area), as computed by surface pressure integration of computational simulation and using constant c_f skin-friction correction.

a two-dimensional, locally adaptive, unstructured Euler computational fluid dynamics (CFD) code.[104] The axisymmetric computations were done in the steady reference frame attached to the projectile (28-mm diameter, 10-deg nose cone and tail cone half-angle), which was modeled as moving at a constant velocity. The detonation wave in a 1-mm-thick layer of explosive bounding the tube (40-mm diameter) was assumed to be initiated on impingement of the conical shock emanating from the projectile nose cone. The detonation in the high explosive itself was not modeled: The flow exiting an oblique CJ detonation in the explosive was used as the in-flow boundary condition at a step prescribed on the edge of the computational domain. The simulated channel was filled with hydrogen gas at 100-atm initial pressure. The explosive was assumed to be slightly porous pentaerythritoltetranitrate (PETN) ($\rho = 1.5$ g/cm^3 and $\rho_{\mathrm{TMD}} = 1.77$ g/cm^3), with the detonation properties given by the equilibrium code Cheetah 2.0 (Ref. 105, $V_{\mathrm{CJ}} = 7.64$ km/s, $P_{\mathrm{CJ}} = 20.5$ GPa, and $V_{\mathrm{sonic}} = 5.83$ km/s). The detonation products were treated as an ideal gas with a constant value of $\gamma = 3.125$ that was fitted to an isentrope computed using Cheetah 2.0. (A value of $\gamma = 3$ is often used for condensed detonation products.[106]) Although the use of an ideal gas equation of state to model the expansion of high explosive detonation products is a gross simplification of the constitutive properties, the modeling of detonation products used in these simulations had been previously used to predict the formation of a precursor shock wave in an explosive-lined channel with considerable success.[107]

The results of the simulations are shown in Fig. 15, in which the flowfield around the projectile (10-deg nose cone and tapered base) is shown. The detonation products expand and drive a strong oblique shock against the projectile. The smearing of the explosive product/hydrogen interface is a result of numerical diffusion. At velocities less than 12 km/s, the detonation products from the explosive liner drove a normal shock wave ahead of the projectile throat, a result analogous to an unstart in a conventional ram accelerator. This undesirable result can be rectified by decreasing the explosive loading or increasing the gas fill pressure. At velocities greater than 12 km/s, steady-state operation was obtained, and the thrust transmitted to the projectile could be calculated by integration of pressure over the projectile surface or by the momentum difference across the control volume (both techniques giving the same value of thrust). The nondimensionalized thrust (net force on the projectile normalized by tube area and initial hydrogen fill pressure) on the projectile is shown in Fig. 16. Note that the values of nondimensional thrust can greatly exceed those obtainable in gas-phase ram accelerators because the energy density in the tube is decoupled from the pressure of the fill gas. Because the SolverII code is an Euler solver, it does not include skin-friction drag in the calculation of thrust. However, using the computational solution of the flowfield over the projectile, it is possible to correct for the effect of viscous drag using a simple friction coefficient, as was done for the model of superdetonative ram accelerator operation in Sec. III.A. Values of skin-friction coefficient were taken over the span of $0.001 < c_f < 0.005$ to bound the expected range. The results suggest that the explosive-lined ram accelerator has a velocity potential on the order of 20 km/s. This maximum velocity can be increased further by increasing the explosive loading and by optimizing the area profile of the projectile. This greatly exceeds the maximum velocity that is achievable with conventional, gas-phase propellant ram accelerators, as well as light gas guns and electromagnetic launchers.

2. *Initiation of Explosives by Shock Waves in Gases*

A key element of the explosive-lined ram accelerator concept is the self-synchronizing of the initiation of the explosive by the shock waves originating from the projectile. Relatively little literature exists on the initiation of detonation in condensed phase explosives by shock waves in gases. Studies done in at the University of Toronto Institute for Aerospace Studies (UTIAS) in the 1960s showed that only sensitive primary explosives, for example, lead azide, and powdered PETN can be initiated by gas-phase detonation.[108,109] Later studies by Grigor'ev et al.[110] using overdriven gaseous detonation waves to initiate porous PETN measured a critical pressure of the gas shock required to initiate the explosive to be in the range of 20–65 MPa, which agrees well with earlier estimates for PETN from the UTIAS studies. This pressure is approximately an order of magnitude lower than the pressure required to initiate porous PETN with a shock wave from another condensed-phase source, that is, a donor charge of a different explosive, suggesting that shock waves in gases may be more efficient at initiating detonation. A recent side-by-side comparison of the initiation of porous PETN by Tanguay and Higgins,[111] however, has shown that the critical shock pressures required for initiation are approximately the same (ranging from 25 to 75 MPa) for a shock transmitted into the explosive by gas and solid sources, with the disparity in the literature being attributed to differences in the duration and profile of the transmitted shock. These pressures are comparable to the pressures reached behind the reflected conical shock emanating from the nose cone in the simulations shown in Fig. 15. The ability of the shock wave merely to initiate detonation may not be sufficient, however. In the critical case of shock initiation, the buildup to detonation in the condensed explosive is a process similar to DDT transition and may take a comparatively long time (on the order of tens of microseconds or longer), which would be too slow relative to the timescales of projectile passage.[112] To observe a coupling effect with the projectile (similar to the coupling observed in the Bakirov and Mitrofanov experiment), the initiation of detonation must be prompt, probably on the order of a microsecond.

A first step toward the demonstrating the explosive-lined ram accelerator concept would be to reproduce the Bakirov and Mitrofanov effect using a safer explosive. PETN appears a promising candidate because it is near the boundary between primary explosives and secondary explosives, making is safe to work with in a laboratory setting but still sensitive enough to be capable of being initiated by a shock wave in gas. To date, however, experiments examining detonation propagation in channels lined with powdered PETN have not observed the high-velocity propagation via a coupling effect.[113,114] Attempts to sensitize PETN via the addition of aluminum have identified ultrafine (nanometric) aluminum as an effective sensitizing agent, decreasing the critical pressure required for initiation by a gas shock to only 5 MPa (Ref. 115). This level of sensitivity may still not be sufficient to permit coupling via prompt initiation of detonation in the explosive lining via the shock wave in the channel (or emanating from the projectile). Research in this area is on going, and the potential exists for new energetic materials to meet the requirement of both safety and prompt initiation.

Recent years have seen the development of new classes of energetic materials, called metastable intermolecular compounds (MIC), that consists of mixtures of nanometric components, for example, a solid fuel and oxidizer.[116] These compounds are mechanically designed, rather than chemically synthesized as is the case with conventional explosives. This development has been motivated, in part, by the need to replace lead-based primary explosives and initiators (lead azide and lead staphnate) with more environmentally friendly compounds. In principle, by tailoring the size, morphology, surfactants, etc., of the compounds, the sensitivity and other properties of the resultant explosive can be engineered. That these compounds are multicomponent means that they maybe capable of being prepared in situ during the process of depositing them on the inner surface of the launch tube. For example, the two components of a binary MIC formulation could be mixed as it is applied to the inner surface of the launch tube. Furthermore, it may not be necessary to use a sensitive explosive for the entire charge; rather, just a surface layer could be sensitized. This could largely remove the safety concerns associated with handling large quantities of primary explosives. Another possibility to prepare a sensitive solid explosive in situ is to condense a gaseous mixture, for example, hydrocarbon and oxygen, onto a cryogenically cooled wall. Such explosives can be extremely shock sensitive and powerful (comparable to conventional high explosives).

Simulations of a ram accelerator tube lined with PETN have been conducted by Kobiera and Wolanski,[117] who also report preliminary experimental investigations of the concept.[118] In their implementation, however, they invoke deflagration (burning) of the PETN, rather than detonation. Thus, the PETN lining the tube wall makes an energetic contribution to what is otherwise a conventional, thermally choked ram accelerator. Using a deflagrating propellant only increases thrust by only 10% and has a negligible influence on the maximum velocity obtainable. This minor benefit makes it difficult to justify the complications of lining the launch tube with high explosive. The same can also be said of proposals to use heterogeneous propellants, such as aluminum powder in gas suspension.[76] The marginal increase in thrust these approaches offer do not seem worth the complexities and safety issues involved and, in the case of a heterogeneous propellant, would likely be extremely destructive to the projectile. The greatest potential for increase in maximum velocity is initiation of detonation in an explosive lining the launch tube wall, but realizing this potential requires prompt initiation by the incident shock wave.

C. Laser-Driven Ram Accelerator

Sasoh has recently proposed the concept of the laser-driven in-tube accelerator (LITA).[119] This concept builds on earlier laser-driven propulsion proposals.[120,121] In the LITA concept, a laser is fired downbore toward the nose of the projectile. This laser light is reflected off of the nose cone and tube wall and is focused onto a small enough region behind the projectile such that breakdown of the working gas occurs. The laser-generated spark becomes opaque, and energy continues to be absorbed as the spark grows and drives a strong blast into the surround gas. This effect is sometimes referred to as a laser-supported detonation. The impact of this blast on the back of the projectile generates positive thrust.

Preliminary experiments by Sasoh et al.[122] have demonstrated the concept using a 70-W pulsed laser to lift a 2-g projectile against gravity (thrust being greater than weight). The efficiencies of these tests (on the order of 300 N of thrust per megawatt of power input) were comparable to demonstration tests of laser propulsion using much larger lasers.

The major impediment this concept faces is the lack of high-power lasers. Currently, the largest available lasers are on the order of 100 kW. If an optimistic efficiency of 10% for converting laser power to projectile thrust is assumed, then the acceleration that can be imparted on a 100-g projectile traveling at 1000 m/s is on the order of 10 g and decreases linearly with increasing velocity. These accelerations are too low by two orders of magnitude to be useful for hypervelocity launching applications. Unlike in the early 1970s, when the prospects for extremely powerful lasers (>1 MW) appeared promising, currently there is little perceived need for larger continuous (or continuously pulsed) lasers.

The laser-driven ram accelerator may find a more functional implementation in combination with the conventional gaseous propellant or explosive-lined ram accelerator concept outlined earlier, where the laser is used to initiate the propellant or explosive. Laser ignition of gaseous combustible mixtures and solid explosives[123–128] is a well-developed technology, and the power requirements are well within current industrial laser capability. The concept of a conical detonation wave in gas stabilized by a pulsed laser has been studied by Carrier et al.,[129] Fendell et al.,[130] and Carrier et al.[131,132] The concept could very well compliment the explosive-lined ram accelerator discussed in Sec. IV.B by providing a means to overcome the problem of providing prompt initiation of an insensitive explosive, synchronized with the passage of the projectile. As has been demonstrated by Renlund et al.[123] and Paisley,[124] PETN can be promptly point initiated by a laser pulse of energy less than 10 mJ. Thus, a 100-kW laser would be able to provide effectively continuous initiation over the explosive lining the inside of the tube, synchronized with the projectile, even at velocities as great as 20 km/s.

V. Conclusions

The experimental results obtained from ram accelerator facilities to date have demonstrated that simple, one-dimensional models of performance are adequate to predict the acceleration of the device. The measured acceleration and final velocity of the projectile are usually within a few percent of the values predicted by the thermally choked and superdetonative models described in this paper. This is sufficient accuracy to determine if the ram accelerator has the potential to achieve a desired level of performance for a particular application.

Where a one-dimensional modeling is inadequate is in determining if the combustion process can stabilize on the projectile. As suggested here, the role of boundary-layer separation induced by shock waves and the pressure rise associated with combustion may be a significant factor. It is clear that any simulation of this effect, beyond the simplistic, analytic modeling presented here, will require multidimensional Navier–Stokes calculations with detailed chemical kinetics coupled to a compressible turbulence model. Such calculations will remain computationally challenging for the foreseeable future, meaning that there is still an important role to be played by experimental investigations.

To date, most studies of ram accelerators have been passive, meaning that there has been no attempt to control the gasdynamic and combustion processes actively by design of the projectile. The problem of separation-induced unstarts in ramjets and scramjets, for example, has been partially addressed by techniques such as boundary-layer bleed and mass flow spillage. It is likely that these techniques will not carry over to ram accelerators; new approaches must be developed. As CFD matures into a predictive tool (similar to contemporary finite element analysis), the ability to design and optimize these concepts becomes feasible. One possibility outlined here is to modify the tube geometry by the inclusion of obstacles, or baffles, to better contain the combustion wave behind the projectile throat.

The large volumetric energy densities of solid explosives would permit projectile velocities well in excess of 10 km/s to be achieved while the projectile itself flies through a low-density, low-molecular-weight core of inert gas. Velocities greater than 10 km/s are of interest to hypervelocity impact, particularly of micrometeorites and orbital debris on spacecraft, and to fundamental equation of state studies. Laser power is unlikely to be sufficient to generate significant projectile accelerations in the foreseeable future, yet this technique may be a useful means to synchronize propellant ignition or explosive initiation.

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