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Use of Jet Interaction for Ignition in Ram and External Propulsion Accelerators

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A new approach is proposed for initiating the chemical processes that are used in several propulsive modes in the ram and external propulsion accelerators. The shock pattern established by ejection of high-pressure gas from the supersonic projectile into the ambient, combustible gas mixture induces the propulsive mode (combustion or detonation). This is fully compatible with the original ram jet-in-tube approach. The present approach does not rely on shock reflections from the barrel, and therefore, is well-suited for use as the ignition source in external propulsion accelerators. As such, it acts in a manner analogous to a physical protrusion suggested previously, but without large drag. The ejected gas has the potential to alter locally the reactive, ambient gas mixture, and therefore, its reactive properties. This would allow the use of a nonoptimal mixture of gases, making unwanted premature ignition less likely. The projectile will need to carry only a relatively small quantity of expendable gas, but the storage volume, system weight, and engineering problems could be considerable. A simple model is developed and used to show the practicality of the method. The results indicate that the jet bow shock can ignite the combustible mixture within a significant radial distance from the body. The method is shown to scale favorably with increasing Mach numbers encountered during the acceleration.

Nomenclature

A = area
C_D = drag coefficient
C_p = pressure coefficient
d = nozzle diameter
h = jet penetration height
M = Mach number
$\dot{m}$ = mass flux
P = pressure
R = shock radius
T = temperature
U = velocity
x = lengthwise coordinate
z = normal coordinate
β = shock wave angle
γ = ratio of specific heats
ρ = density

Subscripts
e = exit conditions
j = pertaining to jet
0 = stagnation conditions
∞ = freestream (undisturbed) conditions

Introduction

THE ram accelerator is a device for accelerating projectiles to velocities vastly exceeding those possible using conventional guns. The concept, first demonstrated by Hertzberg et al.,[1] uses a tube filled with a reactive gas mixture consisting of fuel, oxidizer and, possibly, an inert gas as diluent. The projectile is then injected into the tube at supersonic speed by using a conventional cannon. By careful design of the projectile and the tube, and appropriate choice of the gas combination, a system of shock waves is established between the projectile and the tube such that a chemical reaction takes place only at a predetermined location on the projectile, as shown in Fig. 1a. In the illustration the shock wave from the bow of the projectile is reflected from the barrel at least once (more shock reflections may also be needed) and ideally impinges on the afterbody of the projectile. The passage through the shocks heats and compresses the gas sufficiently to initiate the desired chemical process (in this case supersonic combustion or oblique detonation) downstream of the reflected shock. The high pressure then acts on the projectile afterbody to accelerate it down the tube. It is seen that the concept is similar to a ramjet, except that in the present case the propulsive mixture is the environment through which the projectile flies.

The specific, shock-induced combustion process that occurs is determined by the ambient gas mixture's composition and pressure and the projectile's shape and velocity. For oblique detonation to take place the projectile must travel at a velocity exceeding the Chapman–Jouguet (C–J) velocity of the gas mixture (termed the superdetonative range). Detonation mode is defined here (following Pratt et al.[2]) as the process in which the shock is followed so closely by the supersonic combustion wave that the two become strongly coupled and merge into a single detonation wave. It is also feasible that the supersonic combustion process follows the shock with sufficient delay (induction time) so that it does not strongly affect the shock. The combustion process is thus decoupled from the shock. This is referred to as supersonic combustion, rather than detonation, although by some definitions the two are equivalent. Examples of such supersonic combustion modes can be found in Refs. 3 and 4.

Other propulsive modes utilizing subsonic combustion have been more widely considered and analyzed. These include the mechanically and thermally choked modes discussed in Refs. 1–4. The thermally choked mode, where combustion occurring in the wake of blunt base maintains a normal shock wave on the tapered tail section, is applicable to projectile speeds below the C–J velocity (termed the subdetonative range). This mode is frequently used in the current ram accelerators operating in the subdetonative range.

It is clear that the ignition process must be stationary relative to the projectile, and therefore, this mechanism is strongly

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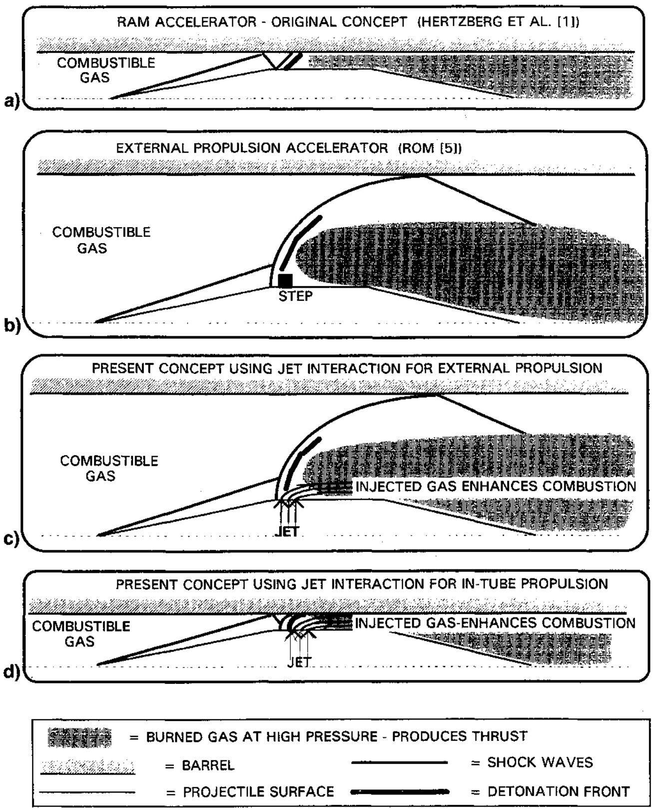

Fig. 1 Examples of established and proposed methods of ignition in the superdetonative speed range.

dependent on the speed, shock strength, and the distance between the projectile and the tube, as well as the reactive atmosphere's composition. Also, many experiments intended to accelerate the projectile into the detonative range have suffered "unstarts"—catastrophic deceleration of the projectile caused by the occurrence of combustion on the forward segment of the projectile. Various possible causes for this are considered, including aerodynamic heating in the boundary layer, deformation of the projectile giving rise to unwanted hot spots, and canting or deformation of the projectile within the barrel. The sensitivity of the combustion process to these geometric factors is especially severe in the ram accelerator because the projectile occupies about 80% of the diameter of the barrel, thus leaving a narrow passage for the gas flow. The volatility of the ambient mixture makes it sensitive to such disturbances.

In order to get away from the tube geometry constraints and thus the need for shock reflections, Rom[5,6] proposed a method in which a shock wave caused by a step in the projectile geometry ignites the mixture, as shown schematically in Fig. 1b. This is possible only if the gas properties and conditions are favorable and the projectile's velocity is in the superdetonative range. The protrusion should be small to limit the extra drag. The minimum step size is the smallest height (about 1 mm) for which a stable combustion will result. The actual step height would be chosen according to the required lateral size of the combustion zone. Therefore, leading-edge shock on the projectile is assumed to contribute to compression and heating of the gas mixture. Since the projectile diameter is two or three times smaller than the tube diameter, this method allows external, tube-independent propulsion. A simpler tube design would be possible both structurally and geometrically, but keeping the projectile centered during the traverse must be assured by aerodynamic means. It is assumed that the guiding fins used in the internal propulsion mode may not be practical because of the large distance between the projectile and the tube.

An excellent and comprehensive review of the state of the art in the ram accelerator technologies can be found in the proceedings of the recent workshop held on this subject.[7]

Present Concept—Ignition Through Jet Interaction

The proposed new concept for achieving ignition and propulsion in external or internal (ram) propulsion accelerators takes advantage of the shock system established when an underexpanded jet is ejected from the projectile moving at high supersonic speeds. This is shown schematically in Fig. 1c for the external propulsion concept and in Fig. 1d for the ram accelerator. This well-known jet interaction problem is encountered when a jet is injected into a supersonic crossflow, see e.g., Spaid et al.[8] A schematic diagram of the flowfield is shown in Fig. 2. The effect of the jet injection into a supersonic main stream is to produce a small, wedge-like upstream separated region characterized by a weak, oblique shock wave and a rise in static pressure, followed by a strong bow shock adjoining the jet. In fact, the jet interaction shock structure and flowfield are highly analogous with those due to the forward-facing step. This is demonstrated numerically in Ref. 9 where the results for the jet and the step flowfields, including wall pressure distributions, are compared. Downstream of the jet location the injected gas blankets the wall while mixing with the ambient stream. The bow shock due to the jet is expected to provide conditions for detonation or deflagration in the gas.

The functional diagram explaining the proposed method is shown in Fig. 3. The upstream separated region and its oblique shock wave (A in Fig. 3) are expected to be small in size and the shock weak enough so that the ambient mixture is not ignited there. The strong jet bow shock produces sufficient heating and compression of the gas to make combustion or detonation possible downstream of a sizable portion of the shock, in regions C and D. In the combustion mode, the bow shock due to the jet must heat the mixture above the ignition point in region B. Under certain conditions, assuming the projectile's velocity to be in the superdetonative range, the shock will give rise to detonation within the gas mixture. In this case the shock and the detonation wave become closely coupled (region B in Fig. 3 will then essentially disappear) and the resulting high pressure accelerates the projectile. Both of these modes are practical in the external and internal (tube-dependent) configurations, using the proposed jet interaction scheme for ignition. Other modes of operation, such as thermally and mechanically choked modes utilizing subsonic combustion, are possible using the present method for the internal propulsion ram accelerator.

The gas mixture may also be made locally more energetic in part of region D in Fig. 3 by injecting one of the constituents

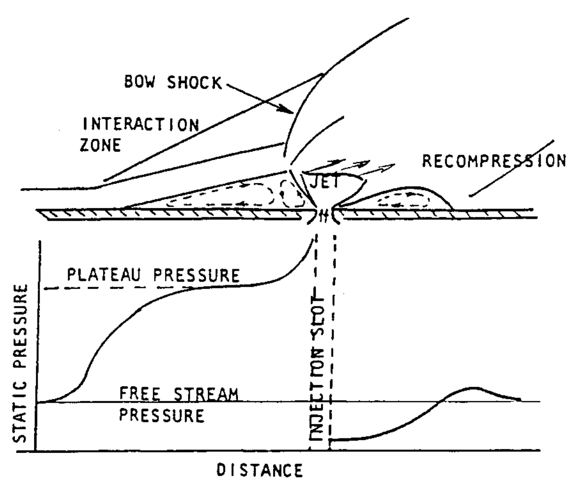

Fig. 2 Schematic diagram of the jet interaction flowfield.

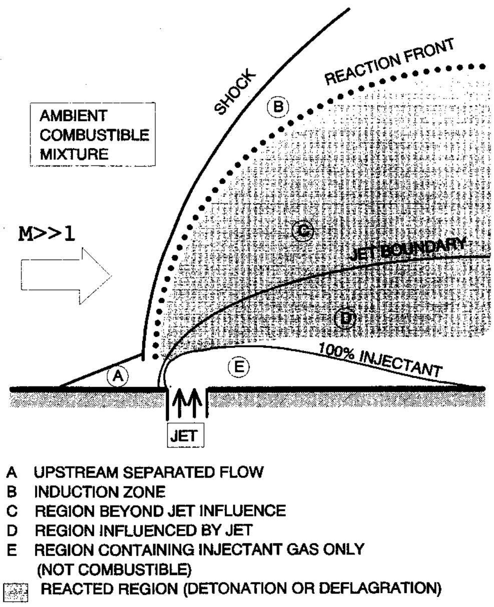

Fig. 3 Schematic diagram of jet-induced combustion.

to alter favorably the equivalence ratio there. Mixing in hypersonic flows is slow, and so the effect of the added component on combustion may be felt only some distance downstream of the injection point. The ambient atmosphere could then be adjusted to make it less sensitive to unintended disturbances, thus gaining an additional degree of freedom for fine-tuning the mixture, especially for long projectiles. This will help to alleviate the problem of "unstarts." The feasibility of enhancing combustion by injection of gas will have to be demonstrated by numerical simulations and experiments. The decision to use fuel or oxidizer as the injectant depends on the ambient gas mixture composition and the projectile design considerations, such as the volume available for injectant gas storage.

In the jet region and in the region immediately downstream of the jet and adjoining the wall (marked E), the injectant concentration (fuel or oxidizer) is too high locally to support combustion or detonation. It, in effect, acts as thermal protection for the projectile. The pressure wave from the lowest portion of the reaction front should affect the projectile only downstream of the jet location because the projectile is traveling faster than the pressure wave in unburned gas and because of the time delay before ignition (induction time), which is significant in the case of combustion. The jet strength should be chosen so that the pressure and temperature downstream of the bow shock due to the jet will be right for igniting the gas mixture along a sufficiently long segment of the bow shock. It is assumed that the projectile travels at a speed exceeding the reaction speed that is mixture and process dependent. This condition is of course necessary to avoid forward propagation of the reaction front. The discrete jets would be distributed circumferentially in a single ring around the projectile in sufficient number (six or more) to provide a continuous shock front. The nozzle geometry need not be circular. Rectangular slots facing the flow with the wide side, or even one continuous slot, could be used and may even offer the advantage of a more uniform shock front.

A very energetic combination of gases for use in the propulsive mixture in the ram accelerator barrels is the $H_2 - O_2$ mixture with the possibility of diluents. The injectant gas could then be hydrogen or oxygen. The detonation velocity of such a mixture would be about 3 km/s, therefore, it would be appropriate only at projectile velocities greater than that if the detonative mode is to be used. For earlier stages of acceleration a nitrogen diluent would be used in the ambient gas. At a still earlier phase a hydrocarbon mixture using CH_4 (having a detonation velocity <2 km/s in air), may be appropriate. The present method would allow the use of hydrogen or oxygen as the injectant for all of the previous ambient mixtures because the jet source travels with the projectile and there is little upstream diffusion. For these reasons the detonation wave could not run ahead of the projectile, even though the downstream mixture (at the rear of the projectile, where the propulsive force is obtained) can be more energetic than the ambient one.

The proposed use of gas jets for inducing ignition should not to the first order affect the drag of the projectile because the momentum lost by the outer flow due to jet interaction is recovered as jet flow momentum turned in the direction of the freestream, as can be seen from control volume analysis. As such, the jet may be the primary means for compressing and heating the gas, which would mean decreased dependence on the projectile's bow geometry. Therefore, slender bow shapes having low-pressure drag can be utilized. Alternately, the jet can be used as the final stage of the compression and heating process. The jets could serve the additional function of providing active control of the projectile after it emerges from the ram accelerator. Jet interaction is useful for controlling super/hypersonic projectiles within the atmosphere because the upstream, higher than ambient pressure region (see Fig. 2) can effectively augment the jet thrust, resulting in control force amplification as shown among others by Brandeis.[9] At very high altitudes such a jet control system would be indispensable because aerodynamic methods for control would be useless. Clearly, for purposes of steering, the system would be larger to accommodate added gas and be mechanically more complicated.

Flowfield Model

The flow variables are estimated in various regions of the flowfield using simple, well-established models. The jet is assumed to be sonic at exit. The shape and location of the bow shock produced by the jet are predicted by using the blast analogy. The conditions behind the bow shock are calculated using the shock relations, once the bow shock curvature and upstream conditions are known. The upstream interaction flowfield is considered unimportant in the present calculations, but could be estimated using empirical approximations. Calculations using this composite model serve to establish the feasibility of ignition by jet interaction. A parametric study tests the sensitivity of the problem to critical variables such as the flight Mach number and the jet injection parameters, mass flux, etc. In the present case, this will be done by considering only the case where the shock and the reacting flow are not coupled. Hence, the analysis is strictly valid for the case of shock-induced combustion, though it is also indicative of what might be expected for the detonative process. The chemical processes involved, including the influence of the jet, will have to be addressed in detail using numerical and experimental methods.

Sonic Jet

For the sonic jet, the jet exit pressure and mass flow rate are related to the chamber stagnation pressure and exit conditions as follows:

$$P_e = P_{oj}[2/(\gamma + 1)]^{\gamma/(\gamma - 1)} \tag{1}$$

$$\dot{m} = \rho_e A_e U_e \tag{2}$$

Jet-Induced Flowfield—Blast Analogy

As has already been noted, the flowfield for a jet in supersonic crossflow is analogous with the supersonic flow over a blunt obstacle. This analogy is especially complete when the shock pattern away from the body is considered. For the present purpose of evaluating the conditions in the flow behind the shock system, the jet can therefore be modeled as a solid obstacle in the way of the high-velocity freestream. Once the jet mass flow rate has been defined from the sonic jet relations (or if the supersonic jet is used by other appropriate means), the size of the equivalent solid obstacle can be related to the jet penetration height. This penetration height is usually defined as the height above the exit port where the jet flow undergoes a normal shock and rapidly turns into the crossflow direction as shown in Fig. 2. Several simple analytical expressions have been derived in the past for the penetration height as a function of the jet and crossflow properties. The result due to Zukosky and Spaid[10] is based on the momentum balance between the normal jet and the supersonic crossflow, assuming isentropic expansion of the jet to the freestream pressure. It is used here in the following form:

$$\frac{h}{d\sqrt{C}} = \frac{1}{M_\infty}\sqrt{\frac{P_{oj}\gamma_j 2}{P_\infty \gamma_\infty C_p}}\left\{\frac{2}{\gamma_j - 1}\left(\frac{2}{\gamma_j + 1}\right)^{(\gamma_j+1)/(\gamma_j-1)} \times\left[1 - \left(\frac{P_\infty}{P_{oj}}\right)^{(\gamma_j-1)/\gamma_j}\right]\right\}^{1/4} \tag{3}$$

where C is the discharge coefficient and C_p corresponds to the stagnation pressure behind a normal shock.

Another version of the same model without assuming isentropic expansion[11] is

$$h = \sqrt{4\dot{m}_j/(\pi C_D \rho U_\infty)} \tag{4}$$

This is just the radius of the equivalent body (one-quarter of a sphere followed by cylinder), arrived at by equating the drag force and the jet exit momentum. There is also the empirical expression due to Cohen et al.,[12] obtained by fitting the data from various experiments:

$$h/d = 1.51\sqrt{(\rho U^2)_j/(\rho U^2)_\infty} \tag{5}$$

This formula basically relates the penetration height to the ratio of jet to freestream momentum.

The shape of the resulting shock wave can now be conveniently estimated using blast wave theory. Using an approach similar to the hypersonic equivalence principle, the blast wave theory models the three-dimensional flow over a blunt slender body as an unsteady cylindrical shock wave propagating from the point of energy release (body axis). The amount of the energy released is linked to the body drag coefficient. For the present needs, the jet issuing into the crossflow can be modeled as an equivalent hemisphere-cylinder. Lukasiewicz[13] derived the closed-form analytical relations for the resulting R as the function of the axial distance x, body diameter (or thickness) z, and the equivalent body's wave C_D. These are presented in their second approximation forms, for the case of the blunt-nosed cylinder:

$$(R/z)/(M_\infty\sqrt{C_D}) = 0.795\sqrt{(x/zM_\infty^2\sqrt{C_D})}[1 + 3.15(x/zM_\infty^2\sqrt{C_D})] \tag{6}$$

It is shown in Ref. 13 that the results obtained with the second approximation to blast-wave theory can be made to fit the experimental data even more closely if the origin of the x axis is displaced from the nose to a point $(2/3)z$ upstream of the nose. This adjustment was not applied in the present calculations. Therefore, the present results may be expected to underpredict the outward extent of the shock.

To complete the analogy, h of the jet is taken as the representative body radius, so that the relationship $z = 2h$ will be assumed for the equivalent body's diameter. It is also noted that the expressions quoted previously are for bodies symmetric about the x axis. For the case of the jet issuing perpendicularly to the surface, only one side of the flow is realized, but, within the limitations of the assumed model, it should be identical to the symmetric case. Finally, the wave drag coefficient is given according to the modified Newtonian theory for the spherical nose body as $C_D = 0.9$.

Now that the bow shock shape is known everywhere the thermodynamic variables downstream of the shock can be found from the general shock relations. The ratios of the flow variables across the shock are given as a function of local β, specific heats ratio, and the upstream M_1 as follows:

Density

$$\frac{\rho_2}{\rho_1} = \frac{(\gamma + 1)M_1^2 \sin^2\beta}{(\gamma - 1)M_1^2 \sin^2\beta + 2} \tag{7}$$

Pressure

$$\frac{p_2}{p_1} = 1 + \frac{2\gamma}{\gamma + 1}(M_1^2 \sin^2\beta - 1) \tag{8}$$

Temperature

$$\frac{T_2}{T_1} = 1 + \frac{2(\gamma - 1)}{(\gamma + 1)^2}\frac{M_1^2 \sin^2\beta - 1}{M_1^2 \sin^2\beta}(\gamma M_1^2 \sin^2\beta + 1) \tag{9}$$

It is now possible to identify the regions where conditions are appropriate for the initiation of a detonation process. Conversely, the jet parameters may be adjusted to produce the correct conditions in the desired flow region.

Upstream Interaction

The jet flowfield, as an obstruction to the external flow, gives rise to upstream flow separation (region A in Fig. 3). This region is a consequence of viscous interaction. Its size depends on the boundary-layer thickness and nature (laminar or turbulent), jet flow rate, and external Mach number. The pressure rise in this region should be small enough to prevent premature ignition. An estimate of the pressures that might be expected within this region was given by Zukoski[14] on an empirical basis for two-dimensional flow as $P/P_\infty = 1 + M_\infty/2$. Given a constant jet source, the upstream separated region shrinks with growing Mach number, but the pressure jump increases. Recent three-dimensional experiments by the present author showed that upstream separation effects are smaller in three dimensions than they are in two dimensions. In addition, the high ambient pressures will decrease the extent of the separation.

Results

The model described in the previous section was first applied for validation purposes to the case of air injection into supersonic freestream (also air). The results are compared with the experimental data[15] for the following conditions. Freestream Mach number 3.3, air density 0.2 atm, injection rate 0.54 kg/s, and jet-to-freestream stagnation pressure ratio 7.9 (sonic jet). The comparison of shock shape is presented in Fig. 4 for various methods of defining the equivalent body, as discussed previously. The results are in reasonable agreement and the simple method of Ref. 11 appears to be preferable for calculating the penetration height. This approach may actually overestimate the penetration height and thus compensate for not using any adjustment in the blast analogy formulation. It should also be noted that the blast theory results are not valid very close to the body's leading edge. This does not hinder the present investigation as the results very close to the origin will not be used.

Two cases are considered as examples of the process in this study. One utilizes gaseous hydrogen of low molecular weight as the injectant, whereas the other considers gaseous oxygen

Table 1 Properties of gases used in the calculations at 300 K

Gas	p, atm	R, J/(kg K)	ρ, kg/m^3	a, m/s
H_2	1000	4157	83.6	1300
	500	4157	41.8	1300
	250	4157	20.9	1300
	100	4157	8.3	1300
O_2	500	260	640	330
	250	260	320	330
	100	260	128	330
$2H_2 + O_2$	10	694	~12	540

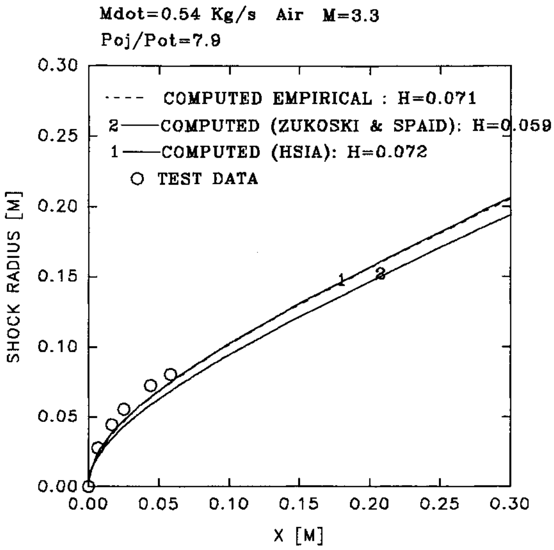

Fig. 4 Shock radius computed using various definitions for penetration height.

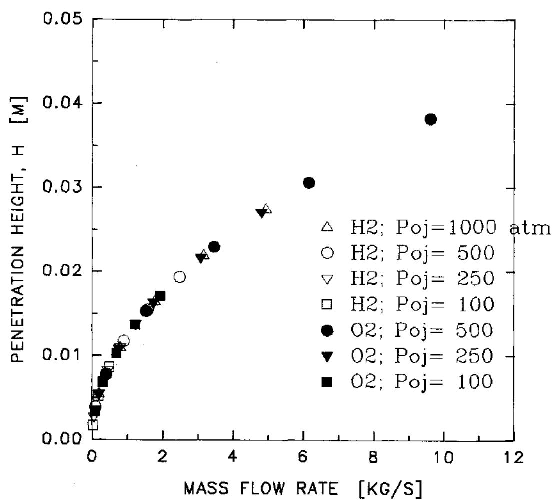

Fig. 5 Penetration height of hydrogen and oxygen jets at various stagnation pressures at $M = 6$ and 10-atm fill pressure.

of relatively high molecular weight as the injectant gas. The ambient atmosphere considered is a stoichiometric hydrogen–oxygen mixture at 10-atm fill pressure in both cases. The parameters considered, aside from the composition of the injectant gas, are its stagnation pressure, mass flow rate, and the Mach number of the projectile. The properties of the gases used are summarized in Table 1 for use in the calculations.

The effects of injectant gas characteristics are examined first. The penetration height is plotted as a function of mass flow rate for hydrogen and oxygen as the injectant in Fig. 5. The freestream Mach number is 6 in both cases. Four stagnation pressures are considered for the hydrogen jet (1000, 500, 250, and 100 atm), whereas three (500, 250, and 100 atm) are presented for oxygen. It is seen that the results for all stagnation pressures fall on one continuous curve. From the continuity of the graphs it appears that mass flow rate is the important parameter and jet stagnation pressure is implicitly included in it. Comparison of the results for the two gases (hydrogen and oxygen) as injectants indicates that their penetration ability is identical for the same mass flow rate. This is not surprising, considering that the present, simple, model does not have molecular weight as a parameter. In reality, there is some advantage in using gas of low molecular weight. The gain associated with using the heavier gas would, therefore, be mainly the smaller required storage volume. This in itself is a major concern in any projectile design. Therefore, oxygen is chosen for the purpose of the present parametric study.

It is now necessary to explore the ability of the bow shock due to the jet to ignite the mixture. Assuming that the projectile nose shock heats the gas to some extent, the jet bow shock needs only to contribute enough heating to ignite the mixture. Clearly this needed amount is a function of the projectile geometry. The curved bow shock due to the jet indicated in Fig. 3 shows that at the innermost shock segment (almost normal shock) the maximum heating would occur. The compression and heating ability of the shock will decrease uniformly as the shock wave curves in the direction of the surface. Therefore, a specific value can be chosen for the minimum acceptable heating ratio, which corresponds to a specific location along the shock. Assuming no interaction with other shocks or strong disturbances that could affect strongly the shape of the shock, this correspondence is unique, and constitutes the upper bound on that portion of the shock that can produce ignition. For the present purpose, with no specific projectile nose configuration in mind, two reference values are chosen as examples of the limiting temperature ratio at the jet bow shock: 1.5 and 2.0. For example, assuming an ignition temperature of 1000 K and the ambient mixture at 300 K, the shock temperature ratio of 2 provides 60% of the needed temperature rise. This is realistic at lower Mach numbers for cones of 15-deg half-angle and/or when the ambient gas mixture has been heated. For more slender projectiles, higher jet shock temperatures will be needed.

The shock radius (distance above the surface along a radial line to the specified shock location) for which the shock temperature ratio is 2, is plotted in Fig. 6 as a function of the mass flow rate for the four jet stagnation pressures mentioned. It is seen that the effective shock segment increases in length with the mass flow rate in the same nonlinear manner, as did the penetration height (Fig. 5). The growth rate is largest at small values of the injection rate. It is also observed that all data calculated using three different stagnation pressures fall on the same graph. The jet pressure enters implicitly through the jet mass flow rate. The oxygen flow rate needed for shock ignition to occur far enough from the body depends on the desired height of the combustion region. In the presently operational ram accelerators, the ratio of the barrel diameter to the projectile diameter is typically between 1.2–1.3. Therefore, a combustion region whose height is 20% of the projectile's radius would be a representative upper limit. As an example, assume a representative projectile radius of 4.5 cm, the time required for acceleration on the order of 0.01 s, and six circumferentially distributed nozzles. Using the temperature ratio of 2 as criterion for ignition limit and 2 cm as the required combustion zone height, the total oxygen consumption of less than 100 g is calculated from Fig. 6. About 250 g of oxygen would be required to assure an effective ignition shock radius comparable with the assumed projectile radius. The weight of the gas is not a significant factor for a body of this size, but the gas storage system volume and weight are. The advantages of using oxygen, having a density 15 times greater than hydrogen, can now be appreciated. It must be

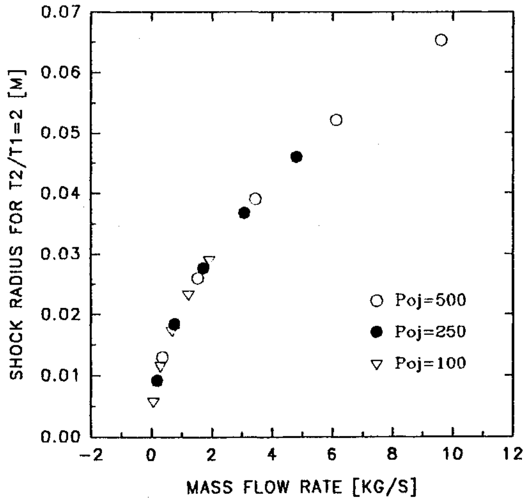

Fig. 6 Variation of critical shock radius (*T2/T1* = 2) with mass flow rate for O_2 jet into $2H_2$ + O_2 mixture. *M* = 6, 10-atm fill pressure.

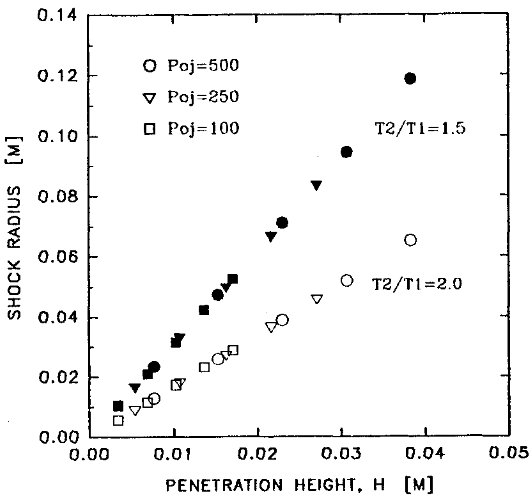

Fig. 7 Dependence of critical shock radius on penetration height for several jet stagnation pressures. O_2 jet into $2H_2$ + O_2 mixture, *M* = 6, 10-atm fill pressure.

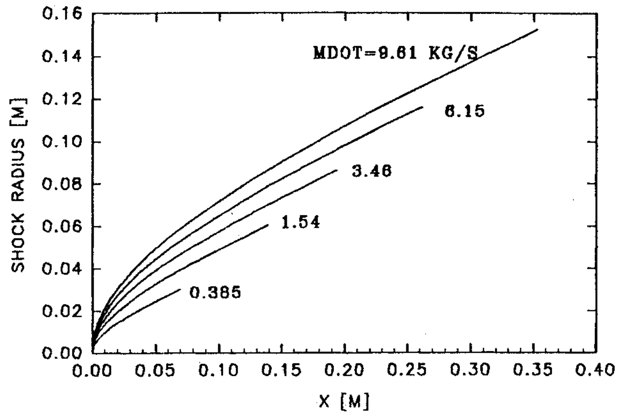

Fig. 8 Shock shapes for several injection rates at *M* = 6 and P_{oj} = 500 atm. O_2 jet into $2H_2$ + O_2 mixture at 10-atm fill pressure.

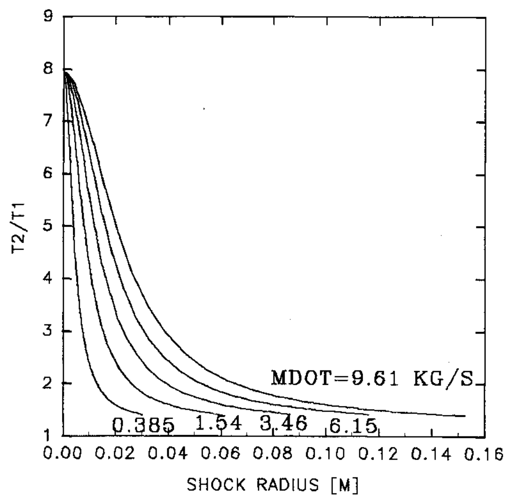

Fig. 9 Temperature ratio across shock as a function of shock radius for several injection rates at *M* = 6 and P_{oj} = 500 atm. O_2 jet into $2H_2$ + O_2 mixture at 10-atm fill pressure.

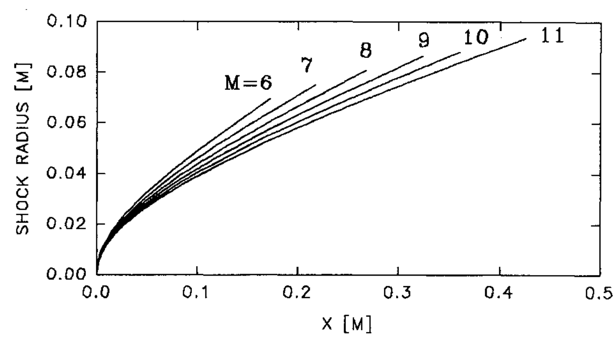

Fig. 10 Shock shapes for several Mach numbers at an injection rate of 1.54 kg/s. O_2 jet into $2H_2$ + O_2 mixture at 10-atm fill pressure.

noted that for practical requirements, it will be sufficient to ignite an even smaller volume of ambient mixture, but using a more stringent ignition temperature ratio limit (3 to 4). More detailed calculations for a realistic configuration are presented in Ref. 16.

The shock radius is plotted as a function of the penetration height in Fig. 7 for the two limiting values of the temperature ratio 2 and 1.5. The effective segment of the shock is seen to increase linearly with the size of the disturbance. This statement is valid for the present case of jet interaction as well as when using a fixed geometrical protrusion (bump), as proposed by Rom,[5,6] to generate the shock. The implications of this will be discussed later. Figure 8 presents the shock shapes for five values of the mass injection rate. The temperature ratio across the shock is shown as a function of shock radius in Fig. 9, for the same values of the injection rate. Each parametric curve represents the variation of shock heating along the corresponding shock plotted in Fig. 8. From such a graph one can choose the needed value for any one of the parameters (mass injection rate, temperature ratio, and shock distance), when the remaining two are specified.

During the launch phase the projectile will be accelerated through a wide range of Mach numbers. This Mach number variation has great implication in the design of the projectile and is therefore carefully examined in the next set of results. The range of Mach numbers considered (between 6–11) in the present ambient gas mixture is representative of the velocities 3000–6000 m/s. The injectant gas in the forthcoming example is oxygen and the rate of injection is 1.54 kg/s. The shock wave shapes calculated for Mach numbers 6–11 are plotted in Fig. 10. The corresponding temperature ratios along these shock waves are shown in Fig. 11. As expected, the temperature ratio across the shock increases with the Mach number at a given shock radius. This is most significant at

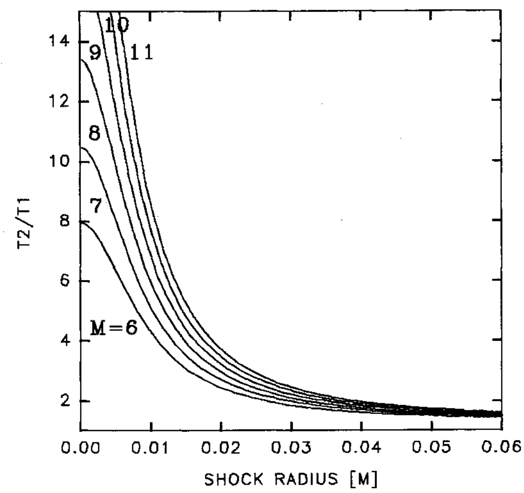

Fig. 11 Shock temperature ratio as a function of shock radius for several Mach numbers at an injection rate of 1.54 kg/s. O_2 jet into $2H_2 + O_2$ mixture at 10-atm fill pressure.

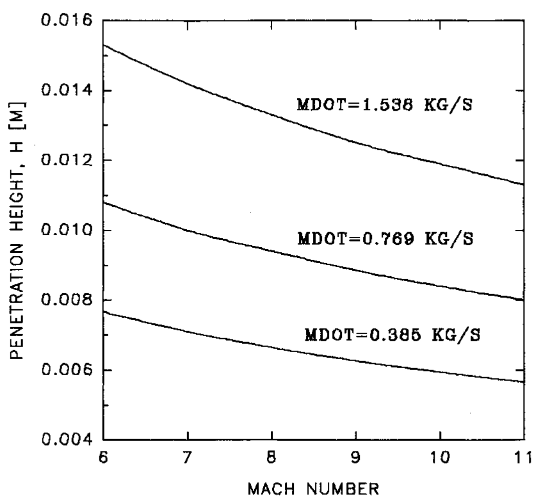

Fig. 12 Jet penetration height as a function of Mach number for three injection rates. O_2 jet into $2H_2 + O_2$ mixture at 10-atm fill pressure.

the inner section of the shock, and least felt far along the shock. For the higher Mach numbers the results for the nearly normal shock segments should not be valid because of the significant nonideal gas effects, for which the present model is unable to account.

The penetration height as a function of the freestream Mach number is plotted in Fig. 12 for three injection rates: 1.54, 0.77, and 0.39 kg/s. The resulting curves show that the penetration height (or, the equivalent body size) decreases monotonously, though not linearly, with Mach number. The corresponding variation of the $T_2/T_1 = 2$ point location along the shocks as a function of Mach number is shown in Fig. 13. As mentioned before, these reference points occur further out along the shock when the Mach number is increased, even though it was seen in Fig. 12 that the penetration height decreases. Therefore, at a constant injection rate the part of the shock wave effective in inducing reaction increases as the projectile accelerates. In an actual launch scenario the injection rate may be expected to decrease because the reservoir pressure decreases with gas expenditure and because the pressure outside increases as the projectile accelerates. At the same time the rate of injectant consumption decreases. This is significant because the lateral size of the reaction region

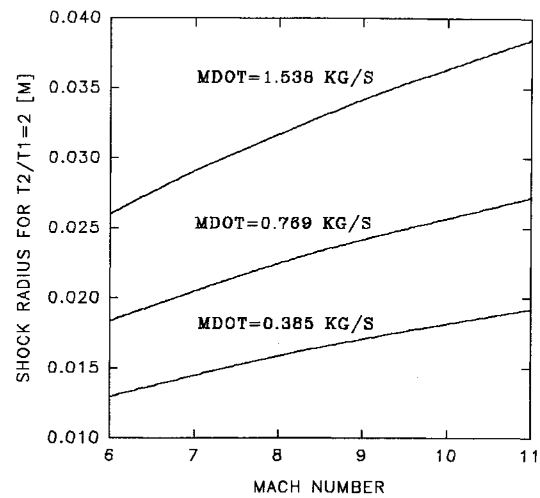

Fig. 13 Shock radius for temperature ratio of 2, as a function of Mach number for three injection rates. O_2 jet into $2H_2 + O_2$ mixture at 10-atm fill pressure.

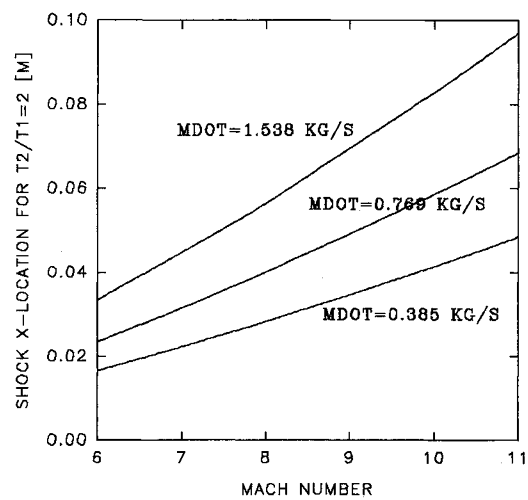

Fig. 14 Axial location of the shock point corresponding to *T2/T1* = 2, as a function of Mach number for three injection rates. O_2 jet into $2H_2 + O_2$ mixture at 10-atm fill pressure.

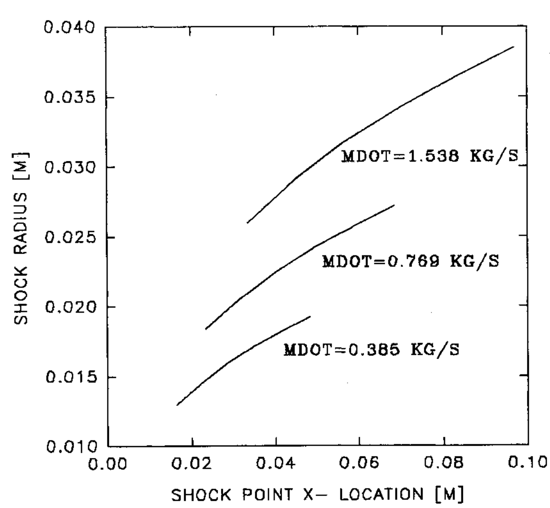

Fig. 15 Trace of the shock point coordinates for *T2/T1* = 2 over Mach number range from 6 to 11 for three injection rates. O_2 jet into $2H_2 + O_2$ mixture at 10-atm fill pressure.

can conceivably be kept constant without any active control during acceleration. In contrast, if a solid obstacle of fixed size is used for the purpose of shock generation, the result is an unneeded growth of the reaction region and a large increase in the projectile's drag.

In addition to the radial changes in size, the ignition region also shifts axially as the shock wave slopes toward the surface with increasing Mach number. This shift is larger in magnitude than the radial change, as evident from the plots in Fig. 14 showing the variation of the x coordinate of the limiting temperature ratio point at the shock with Mach number, and in Fig. 15 that shows the $x - r$ trace of these points as the Mach number changes. The axial coordinate of the limit points is important because it influences the length of the projectile. The projectile should be sufficiently long to benefit fully from the increase in the size of the reacting region as the high pressure is felt by the projectile surface only some distance downstream. The projectile's geometry will, therefore, be influenced by the maximum Mach number expected, both for the conventional ram accelerator and for the external propulsion version.

Conclusions

A novel method was introduced for triggering the chemical reaction, either combustion or detonation, in a reactive gas mixture utilized in the accelerator system. In the proposed method the projectile carries internally a small amount (in proportion to its mass) of gas at high pressure that is released continuously into the environment during the acceleration process. The bow shock produced by the jet heats and compresses the ambient gas mixture sufficiently for the reaction to take place, without the drag caused by an analogous bump. At the same time, the released gas, which may be fuel, oxidizer, or inert, has the ability to alter the mixture downstream in such a way as to make it more energetic, thus enhancing the reaction process. This control of the mixture within a limited region allows the use of a less volatile ambient gas mixture, which may help prevent premature, upstream ignition. The present method is applicable to the various modes of propulsion proposed for the barrel-dependent accelerator. However, only the supersonic combustion modes (coupled and decoupled) are applicable to the external propulsion (barrel-independent) configuration.

Analysis shows that it is possible to ignite the combustible mixture in passage through the jet bow shock and to promote reaction in a region whose size depends on the conditions in the gas ahead of the jet and on the strength of the jet itself. Greater temperature and pressure rise across the projectile's nose shock permits smaller jet strength for reaction to take place over a defined region. For projectiles used in the current experiments, weighing in the range of kilograms with a radius of 4.5 cm, a typical amount of gas required would be on the order of 100 g.

It has also been shown that as the Mach number increases, the strength of the jet required to maintain a constant size reaction zone can be expected to decrease. This fits neatly with the fact that as the gas is being depleted, the pressure, and hence, the jet strength decreases naturally if a prepressurized source is used. The reaction front can be envisioned as being anchored to the jet, that acts as a flameholder. Therefore, the present method has an advantage of rendering the projectile design less Mach number dependent than the currently used method utilizing multiple shock reflections to achieve reaction, for which the ignition location can move considerably along the projectile's surface during acceleration. It is conceivable that the jets could be used to enhance the stability of the projectile within the barrel. After the projectile has exited the accelerator the use of jets for vehicle control is a very attractive choice.

The major drawback is the added engineering problems in design and integration of the gas storage and ejection system. It is necessary to investigate the various ideas put forward, especially those pertaining to the reaction process, in much greater detail than the preliminary analysis presented in this article, in order to prove feasibility and efficiency. Of special interest is the study of mixing and combustion/detonation in the region of the flow in the vicinity of the jet. Detailed numerical investigation followed by experiment would achieve that goal.

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References

[1]Hertzberg, A., Bruckner, A. P., and Bogdanoff, D. W., "Ram Accelerator: A New Concept for Accelerating Projectiles to Ultrahigh Velocities," *AIAA Journal*, Vol. 26, No. 2, 1988, pp. 195–203.

[2]Pratt, D. T., Humphrey, J. W., and Glenn, D. E., "Morphology of Standing Oblique Detonation Waves," *Journal of Propulsion and Power*, Vol. 7, No. 5, 1991, pp. 837–845.

[3]Bogdanoff, D. W., "Ram Accelerator Direct Space Launch System: New Concepts," *Journal of Propulsion and Power*, Vol. 8, No. 2, 1992, pp. 481–490.

[4]Bruckner, A. P., and Knowlen, C., "Overview of Ram Accelerator Technology," National Shock Wave Symposium, Inst. of Fluid Sciences, Tohoku Univ., Sendai, Japan, Jan. 1993.

[5]Rom, J., "Method and Apparatus for Launching Projectile at Hypersonic Velocities," U.S. Patent 4,932,306, June 1990.

[6]Rom, J., and Avital, G., "The External Propulsion Accelerator: Scramjet Thrust Without Interaction with Accelerator Barrel," AIAA Paper 92-3717, July 1992.

[7]*Proceedings of the 1st International Workshop on Ram Accelerator (RAMAC)*, ISL–French–German Research Inst., Saint Louis, France, 1993.

[8]Spaid, F. W., and Zukoski, E. E., "A Study of the Interaction of Gaseous Jets from Transverse Slots with Supersonic External Flows," *AIAA Journal*, Vol. 6, No. 2, 1968, pp. 205–212.

[9]Brandeis, J., "Numerical Study of Jet Interaction at Super- and Hypersonic Speeds for Flight Vehicle Control," *Proceedings of the 18th Congress, International Council of the Aeronautical Sciences*, Beijing, PRC, 1992 (ICAS Paper 92-4-9.1).

[10]Zukoski, E. E., and Spaid, F. W., "Secondary Injection of Gases into a Supersonic Flow," *AIAA Journal*, Vol. 2, No. 10, 1964, pp. 1689–1696.

[11]Hsia, H. T.-S., "Equivalence of Secondary Injection to a Blunt Body in Supersonic Flow," *AIAA Journal*, Vol. 4, No. 10, 1966, pp. 1832–1834.

[12]Cohen, L. S., Coulter, L. J., and Egan, W. J., "Penetration and Mixing of Multiple Gas Jets Subjected to a Cross Flow," *AIAA Journal*, Vol. 9, No. 4, 1971, pp. 718–724.

[13]Lukasiewicz, J., "Blast-Hypersonic Flow Analogy Theory and Application," *American Rocket Society Journal*, Sept. 1962, pp. 1341–1346.

[14]Zukoski, E. E., "Turbulent Boundary Layer Separation in Front of a Forward Facing Step," *AIAA Journal*, Vol. 5, No. 10, 1967, pp. 1746–1753.

[15]Brandeis, J., and Gill, Y., "Experimental Investigation of Side-Jet Steering for Missiles at Supersonic Speeds," AIAA Paper 95-0316, Jan. 1995.

[16]Brandeis, J., "Ram Accelerator Utilizing Active Projectile," AIAA Paper 95-0288, Jan. 1995.