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Ram Accelerator Utilizing Active Projectile

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A chemical-propulsion accelerator (either ram- or external-propulsion) system, utilizing a novel, active-projectile concept is proposed. The projectile comprises the mechanism for compression, storage, and release of high-pressure fluid, that may be either the fuel or the oxidizer used in the ambient combustible gas mixture or inert gas. The shock pattern established by ejection of high-pressure gas from the supersonic projectile into the ambient, combustible-gas mixture serves to ignite the mixture through shock heating and compression, and therefore, to induce the desired propulsive mode (combustion or detonation). The ejected gas then serves to alter locally the ambient mixture, and therefore, can enhance its reactive properties. The present method also offers potential application in future aerospace vehicles that will utilize external propulsion modes. A simple model is used to show the practicality of the method and to estimate the lateral size of the combustion zone. The results show that the jet bow shock can ignite the combustible mixture within a radial distance from the body comparable with the barrel radius used in the present ram accelerators. The size of the combustion zone is shown to scale favorably with increasing Mach numbers encountered during the acceleration. The amount of the injectant gas needed is shown to be small.

Introduction

AN improvement to the present ram- and external-propulsion accelerator concepts based on ignition through jet interaction is proposed. It eliminates some of the drawbacks of the presently known systems and offers more flexibility and possible extensions to future propulsion systems. This article presents this concept and demonstrates its feasibility, based on simple analytical models. On these bases the novel elements are examined parametrically. No overall propulsive performance calculations are attempted, although an estimate of expected velocity increment is presented for a specific example.

The ram accelerator is a device for accelerating projectiles to velocities vastly exceeding those possible using the 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. The chemical reaction takes place only at the 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 two 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's afterbody to accelerate it down the barrel.

The factors determining what type of combustion mode is initiated by the shock are the ambient gas mixture's composition and pressure and the projectile's shape and velocity. For the 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 feasible also 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 mechanically and thermally choked combustion have been more widely considered and analyzed.[1–4]

It is clear that the ignition process must be stationary relative to the projectile, and therefore, this mechanism is strongly dependent on the speed, shock strength, and the distance between the projectile and the tube, as well as the reactive atmosphere's composition. In all systems presently existing, the accelerator barrel must be sufficiently narrow to produce the reflected shock (or detonation) waves. These may be called internal propulsion systems. In order to get away from the constraints of the tube geometry, and thus, the need for shock reflections, Rom[5] proposed an accelerator that has a barrel wide enough not to produce reflection of shock waves in the vicinity of the projectile, but instead, the detonation wave is produced by a shoulder portion in the form of a step, as shown schematically in Fig. 1b. This method allows, in essence, a tube-independent propulsion mode, called an external propulsion system.

The ram-accelerator concepts described previously are not fully satisfactory. For example, the internal propulsion systems require potentially destructive physical contact between the projectile and the barrel, whereas the obstacle essential for the external-propulsion system described by Rom[5] produces a significant amount of unwanted drag, which the present method may avoid or at least greatly reduce. Many experiments intended to extend the velocity range into detonative range have suffered unstarts, catastrophic deceleration of the projectile. This may be caused in part by preignition on the forward segment of the projectile. The jet interaction accelerator concept put forward in this article may alleviate the problem of preignition through local control of the mixture in the reaction zone only.

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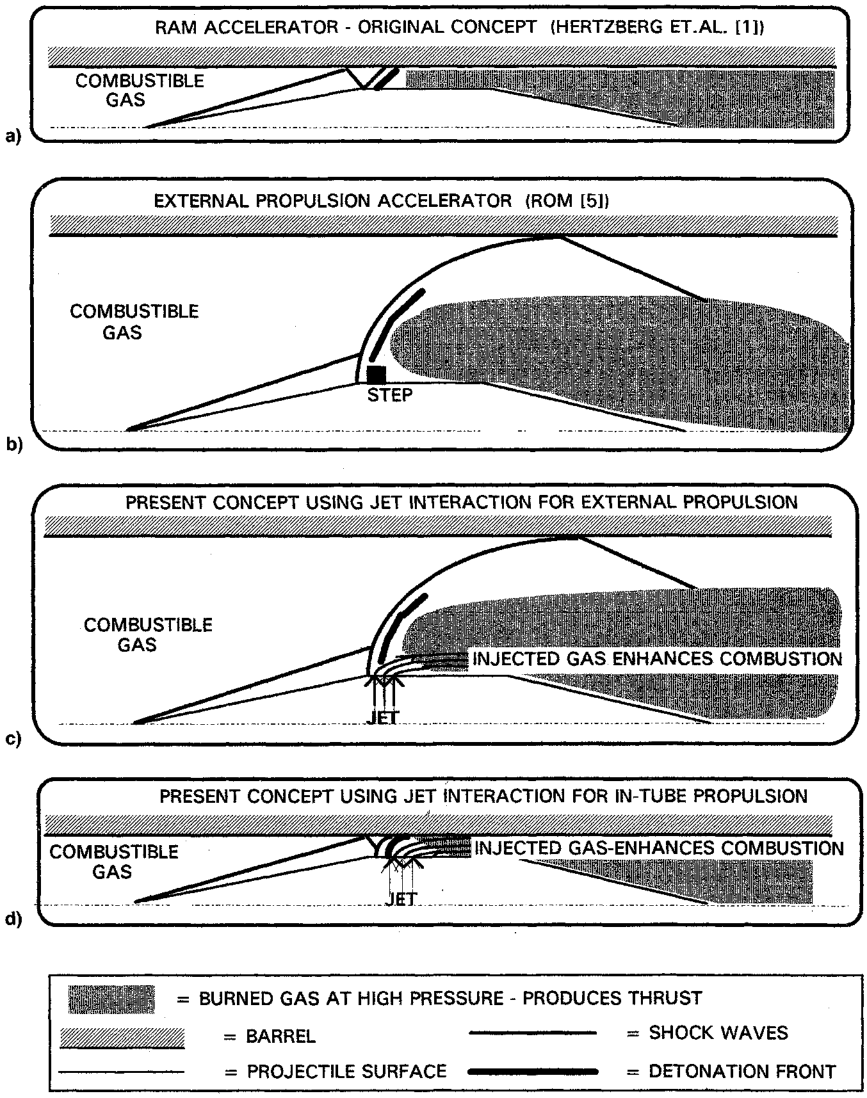

Fig. 1 Examples of established and proposed methods of ignition in the superdetonative speed range.

Hybrid Concept: Ignition Through Jet Interaction

The proposed new hybrid concept for achieving ignition and propulsion in ram accelerator takes advantage of the shock system established when an underexpanded jet is ejected from the projectile moving at high supersonic speeds. The concept is applicable to the external propulsion system that is tube independent, as well as to the internal propulsion system. This is shown schematically in Fig. 1c for the external propulsion, and in Fig. 1d for the more conventional barrel-dependent concept. The jet interaction principle utilized here is encountered when a jet is injected into a supersonic crossflow (see, e.g., Spaid et al.[6]). The jet interaction gives rise to a strong, curved bow shock wave ahead of the jet, as shown in the functional diagram in Fig. 2. In fact, the jet interaction shock structure and flowfield are highly analogous with those because of the forward-facing step as shown numerically by Brandeis.[7] The strong bow shock produces sufficient heating and compression of the gas to make combustion or detonation possible along a reaction front that follows the shock and the induction zone, B). For some combustion modes the induction zone may be significant, whereas for the detonation process the shock is closely coupled with the reaction (detonation) wave. The injected gas jet mixes with the ambient gas within a zone enclosed between two boundaries, marked jet boundary and 100% injectant in Fig. 2. Within this region the mixture may therefore be made locally more energetic by injecting a

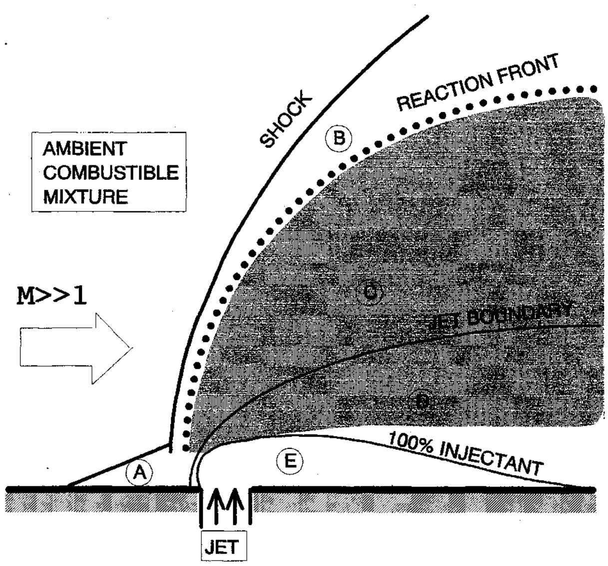

Fig. 2 Schematic diagram of the jet-induced combustion. A), upstream separated flow; B), induction zone; C), region beyond jet influence; D), region influenced by jet; E), region containing injectant gas only (not combustible); and ■, reacted region (detonation or deflagration).

volatile fuel such as hydrogen, or an oxidizer, such as oxygen. The equivalence ratio is thus locally altered in such a way as to produce a more energetic reaction, allowing the use of a less than optimal ambient mixture and, consequently, alleviating a possible cause of unstart. Below the lower limit, the concentration of the injectant is so high as to inhibit any reaction, thus shielding the surface of the projectile from the heat. The reaction can therefore take place only within the shaded region B) and part of C) in Fig. 2. The triangular upstream separated region A) and its oblique shock wave are expected to be small in size and the shock weak enough so that the ambient mixture is not ignited there.

The bow shock due to the jet is expected to provide conditions for detonation or deflagration in the gas by heating the mixture above the ignition point. 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. Supersonic combustion can then take place downstream of the jet and the resulting high pressure would act on the tapered tail of the projectile to produce thrust. Under certain conditions and assuming 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 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 hybrid accelerator, combining the ram or external propulsion, and the jet interaction concepts.

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, as marked in Fig. 2. 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. A very energetic combination of gases is the $2H_2 - O_2$ mixture with the possibility of diluents. The injectant gas could then be hydrogen, oxygen, or inert. 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 of <2 km/s in air) may be appropriate. The present method would allow use of hydrogen or oxygen as 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 offers several additional advantages. First, it should not 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. The jets may therefore be the primary means for compressing and heating the gas, which would mean that the method is less dependent on the projectile's bow geometry, and slender bow shapes having low pressure drag can be utilized. Furthermore, the jets can be utilized to impart spin to the projectile, needed for stability in the external propulsion mode. Lastly, the jets could serve as an effective means of control for the projectile in free flight. Examining the further-term system requirements will reveal that some sort of steering system may be necessary. Here, the use of jets has its own merits and the two requirements could be combined into one system.

Combustion Region Characteristics

Several simple phenomenological models were put together to establish the feasibility of using the jet interaction for ignition. The model and the results obtained are reported in detail by Brandeis[8] and will only be outlined here. In essence, the model serves to link the gas heating and compression by the shock to the parameters defining the jet that causes the shock. The simplest model used for estimating the penetration height of the jet is not sensitive to the effect of the gas' molecular weight. In reality, a light gas such as hydrogen will have an advantage in this respect over a heavier gas. The high-pressure 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 approach used is one of examining the magnitude and extent of the disturbance caused by the bow wave preceding the jet. It constitutes a direct indication of ignition ability of the bow shock from the jet when the decoupled, shock-induced combustion mode is considered as the energy release mechanism. For shock-induced detonation, the present analysis gives only an indirect indication of this ability, since due to the coupled nature of the two processes, the downstream conditions have to be considered by assuming a C–J detonation. No mixing or chemical calculations are attempted.

Calculations with the composite model were done to estimate the variation of flow parameters such as pressure, temperature, and density across the shock due to the changes in the jet parameters and the flight Mach number. 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 ambient atmosphere assumed in these illustrative calculations is the stoichiometric hydrogen–oxygen mixture at 10-atm fill pressure. The injectant gas is molecular oxygen. The gain associated with using the relatively heavy oxygen is the smaller required storage volume. This in itself is a major concern in any projectile design. Another consideration affecting the choice of the injectant gas is its effect on the reactivity of the mixture. Other parameters considered are the jet's stagnation pressure, mass flow rate, and the Mach number of the projectile.

Figure 3 presents the shock shapes for five values of the mass injection rate. Then, the temperature ratio across the shock is shown as a function of shock radius in Fig. 4, for the same values of the injection rate. Each parametric curve rep-

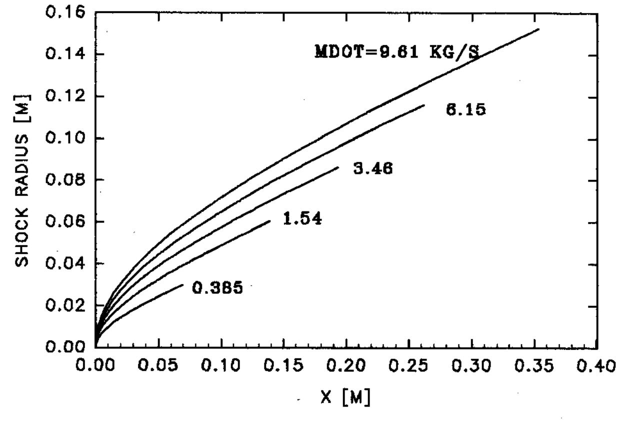

Fig. 3 Shock shapes for several injection rates at $M = 6$, $Poj = 500$ atm, O_2 into $2H_2 + O_2$ at 10 atm.

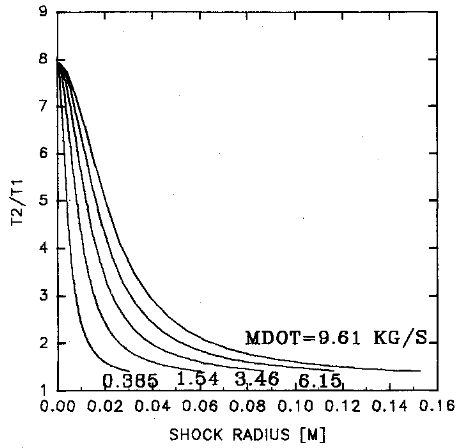

Fig. 4 Temperature ratio across the shock vs shock radius for several injection rates at $M = 6$, $Poj = 500$ atm, O_2 into $2H_2 + O_2$ at 10 atm.

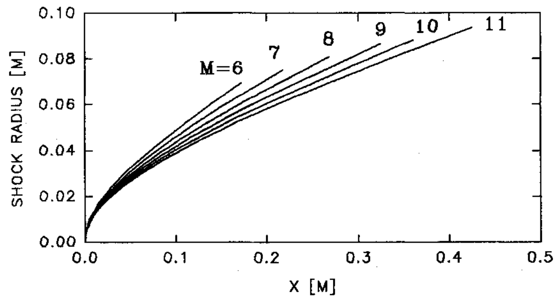

Fig. 5 Shock shapes for several Mach numbers at injection rate of 1.54 kg/s, $Poj = 500$ atm, O_2 into $2H_2 + O_2$ at 10 atm.

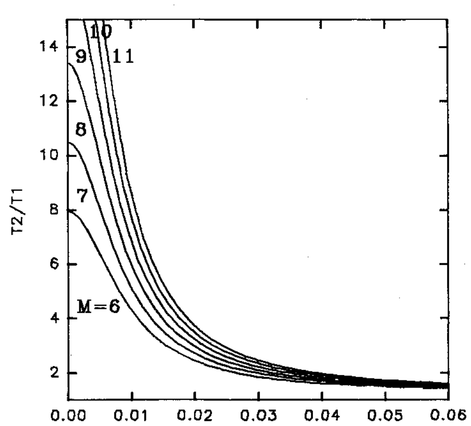

Fig. 6 Shock temperature ratio vs shock radius for several Mach numbers at an injection rate of 1.54 kg/s, $Poj = 500$ atm, O_2 into $2H_2 + O_2$ at 10 atm.

resents the variation of shock heating along the corresponding shock plotted in Fig. 3. 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. Assuming that bow shock due to the projectile nose heats the gas to a considerable extent, the jet bow shock needs only to contribute enough additional heat to ignite the mixture. 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 for which ignition may be expected, that corresponds to a specific location along the shock. This constitutes the upper bound on that portion of the shock that can produce ignition.

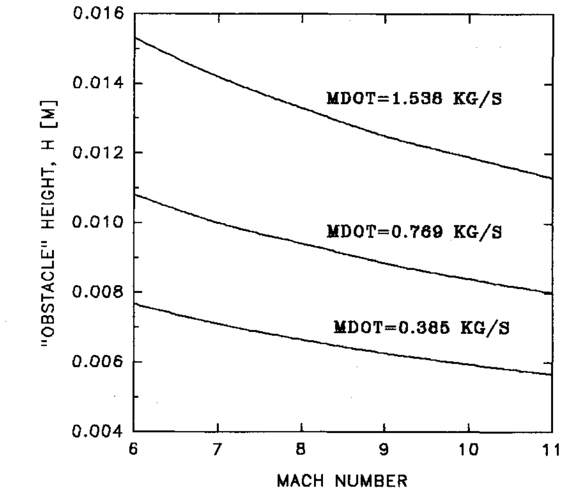

Fig. 7 Equivalent body diameter as function of Mach number for three injection rates, O_2 into $2H_2 + O_2$ at 10 atm.

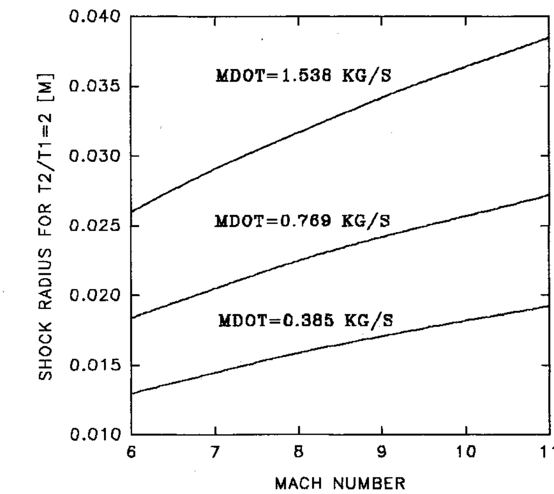

Fig. 8 Shock radius corresponding to $T_2/T_1 = 2$ vs Mach number for three injection rates, O_2 into $2H_2 + O_2$ at 10 atm.

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. 5. The corresponding temperature ratios along these shock waves (within the centerplane passing through the jet) are shown in Fig. 6. As expected, the temperature ratio across the shock increases with the Mach number at a given shock radius. This is most significant at the inner section of the shock and felt the least 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. Also, the jet strength will dissipate away from the centerplane, where the transverse curvature is large.

The effective obstacle size, based on the jet penetration height, is plotted as function of the freestream Mach number in Fig. 7 for three injection rates: 1.54, 0.77, and 0.39 kg/s. The resulting curves show that the penetration height (or by analogy, the equivalent body size) decreases monotonously, though not linearly, with Mach number. The corresponding variation of the vertical coordinate along the shock where $T_2/T_1 = 2$, as a function of Mach number, is shown in Fig. 8. This reference point, chosen as an example of heating ratio that may be required of the jet bow shock, occurs further out along the shock when the Mach number is increased, even though it was seen in Fig. 7 that it corresponds to a decrease of the penetration height. Therefore, at 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 external pressure increases as the projectile accelerates. This is significant, because a possibility arises naturally, without any manipulation, of keeping the lateral size of the reaction region constant during the acceleration. At the same time the rate of injectant consumption decreases. In contrast, if a solid obstacle of fixed size were used for the purpose of shock generation, it would result in 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 Mach number increases, and consequently, the shock wave slopes toward the surface. The axial coordinate of the limit point is important because it influences the length of the projectile.

Jet Interaction Hybrid Accelerator

A hybrid accelerator system utilizing the jet interaction principle for ignition and mixture enhancement is described in this section. In its overall appearance the system, shown schematically in Fig. 9, does not differ from the existing systems. It employs a preaccelerator gun to launch the projectile at supersonic speed, a chamber for discarding the expendable parts, and several ram accelerator segments, filled with various mixtures, to facilitate various modes of propulsion, as needed. A mixed system is conceivable, where the first stages would provide for internal propulsion modes that are more appropriate at lower speeds, whereas at later stages it would be wide barrels for external propulsion to accommodate detonative drive.

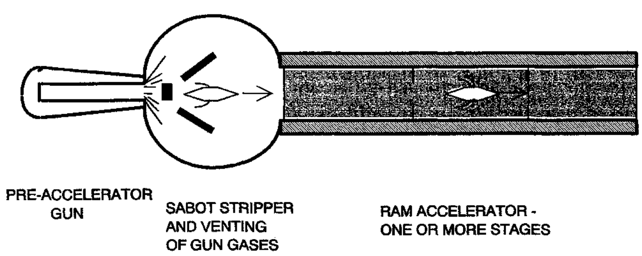

Fig. 9 Schematic diagram of the accelerator system. ■, combustible gas mixture.

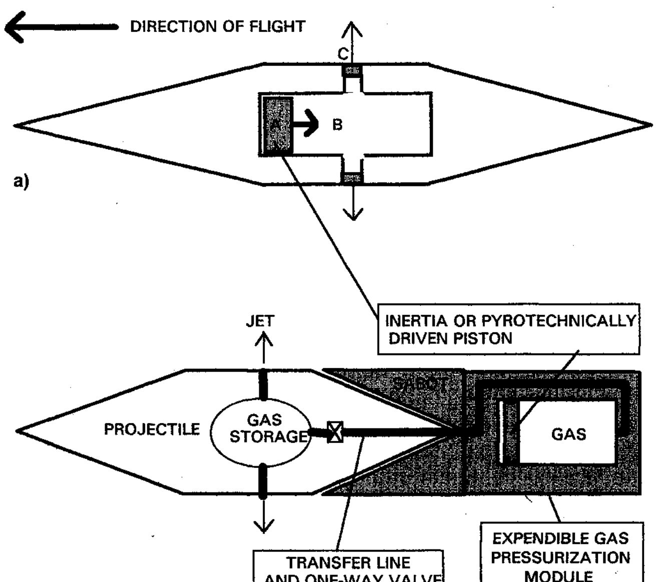

Fig. 10 Several methods for storage, pressurization, and release of the injectant gas: a) projectile-contained gas pressurization and storage system and b) external gas pressurization and transfer system.

The main element of the proposed system, that differentiates it from other, known, concepts, is the projectile. The projectile's external configuration depends on various factors and may not differ from other designs. Within the projectile, a chamber is provided for storing the gas under high pressure. The gas will be compressed to the necessary pressure through one of several possible means:

1) It can be preloaded at the necessary pressure.

2) It can be loaded at an elevated pressure and compressed to the final state by a piston activated either inertially during launch from the preaccelerator gun or pyrotechnically before launch, as shown in Fig. 10a. This still requires a considerable onboard storage volume, even for the small amount of gas that is needed.

3) An alternative may be considered, shown in Fig. 10b, where the projectile is equipped with an expandable component that contains the preloaded gas, and at the same time also serves as a pusher plate used in the current ram accelerators. This component is connected to the storage chamber within the projectile by a transfer line comprising a one-way valve, through which the mechanically compressed gas is supplied to the projectile either before or during launch, as described for the prior case. Still another option is the use of a gas generator.

The generic projectile shown here is a cone–cylinder–cone configuration. The shock-induced mechanism explained in principle in Fig. 2, must now be implemented for the actual configuration to provide a uniform ignition and combustion

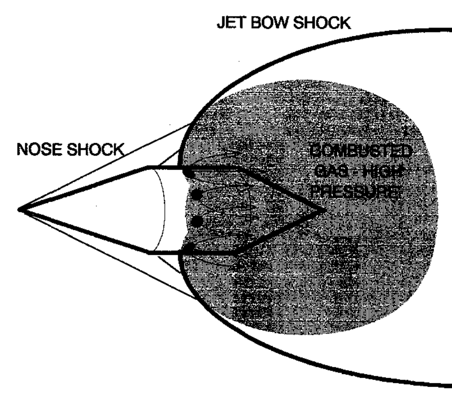

Fig. 11 Schematic diagram of the projectile undergoing acceleration in the proposed mode.

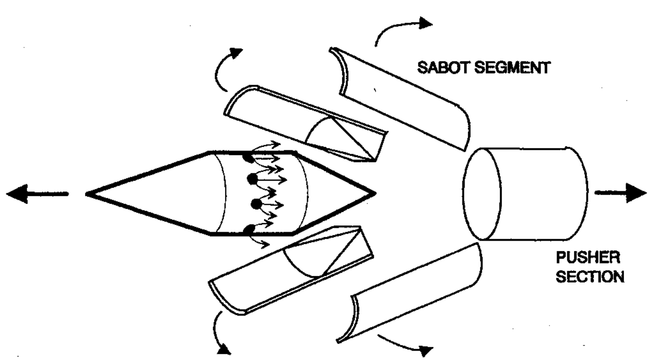

Fig. 12 Sabot separation and activation of the jets upon leaving the preaccelerator gun.

around the projectile. To provide a continuous shock front, the discrete jets must be distributed circumferentially in a single ring around the projectile in sufficient number (six or more). As seen in Fig. 11, a three-dimensional, undulating shock front can be expected. As more jets are used, the shock curtain assumes a more regular shape. Moreover, 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 offer the advantage of more uniform shock front. During the gun launch the projectile is enclosed within a protective sabot, which also serves to plug the jet exit ports. The high pressure from the chamber within the projectile helps to cast off the sabot, thus activating the jets, as shown in Fig. 12.

Application to Characteristic Configuration, an Example

The method described in previous sections is now applied as an illustrative example, to a typical configuration. The projectile chosen has a conical forebody followed by a cylindrical shoulder section containing the jets, as shown in Fig. 13. It is assumed for reference that the projectile diameter is 91.5 mm, and its mass is 4.5 kg. These dimensions are identical to those for the Army Research Lab (ARL) 120-mm ram-accelerator facility.[9] (The accelerator length in that facility is presently 23.5 m.) The afterbody may be conical or partly truncated shaped. The conical forebody vertex angle is chosen according to need. Larger cone angle results in stronger conical shock, thus reducing the strength of the bow shock due to the jet (and therefore, the jet strength) that is required for ignition. On the other hand, for reasons of drag reduction as well as reduction of the premature ignition risk, it is desirable to have the conical forebody section as slender as possible. Therefore, a range of possible cone angles and jet injection rates will be examined parametrically.

The ambient, combustible mixture is again taken for the illustrative purpose as stoichiometric hydrogen–oxygen combination and the injectant gas is oxygen. In reality, the ambient mixture would almost certainly include diluents such as nitrogen. It is assumed on the basis of published data (e.g., Ref. 10), that the ambient gas mixture ignition should occur within the range of temperatures of 1300–1500 K. Assuming an ambient gas temperature between 300–400 K, this gives a minimum value of 3.25 for the total temperature ratio T_2/T_∞ (see Fig. 13) required for ignition, while the maximum is 5.

It is appropriate to examine first the effect due solely to the conical forebody. Three cone half-angles, σ = 5, 10, and 15 deg are considered. The temperature ratio (T_1/T_∞) across the shock produced by each of these cones is shown plotted against the Mach number in Fig. 14. It is seen that at low Mach numbers all three cones contribute only a small amount at best to the total temperature rise needed for ignition, as defined earlier. Above M = 10, the 15-deg cone would be impractical, because of the high possibility of igniting the mixture, thus leading to unstart. The 5-deg cone is seen to have little effect in heating the gas within the Mach number range considered.

The contribution required of the jet bow shock to bring the temperature of the mixture to the level required for ignition is $T_2/T_1 = (T_2/T_\infty)/(T_1/T_\infty)$. This ratio is plotted against the Mach number in Fig. 15 for the maximum (most restrictive) value of $T_2/T_\infty = 5$, and for the minimum value of that quantity, 3.25, in Fig. 16. It is readily observed from both graphs that the needed jet contribution decreases fast with the rising Mach number, as the contribution of the conical body increases. Also, as expected, the required jet contribution decreases with increasing cone angle. From the point of view of the jet injection system, the effect of the 5-deg conical forebody is marginal and the jet will have to work almost as hard as if it were the sole agency in causing ignition. The 15-deg cone is probably the upper limit on the allowable cone angle for Mach numbers exceeding 10. Therefore, it appears that the range of cone angles chosen is realistic.

Next, it is necessary to investigate the implications of the previous discussion on the actual jet requirements and effectiveness. For this reason, in Fig. 17 the more restrictive jet shock temperature ratio values (from Fig. 15) for the 5- and 10-deg cones are replotted onto a segment of the graph from Fig. 6. The jet alone case (cone of 0 deg) is also shown for reference. The abscissa is the effective shock radius away from the body and the shock temperature ratio plots are shown for Mach numbers from 6 to 11. The jet injection rate in this example is 1.54 kg/s and the jet stagnation pressure is 500 atm. From Fig. 17 it is seen that at M = 6 the jet following the 5-deg cone would induce combustion up to about 10 mm from the surface, while with the 10-deg cone that value would be about 12 mm. At M = 11, the region would grow in size to 19 and 29 mm, respectively, for the two cases. These values are significant and encouraging. They were derived for the

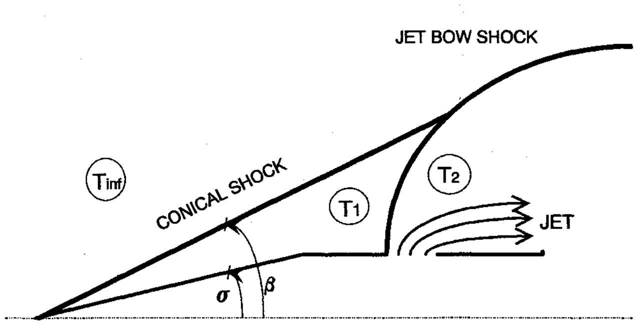

Fig. 13 Definition of parameters used for calculating the required jet strength for conical nose projectile.

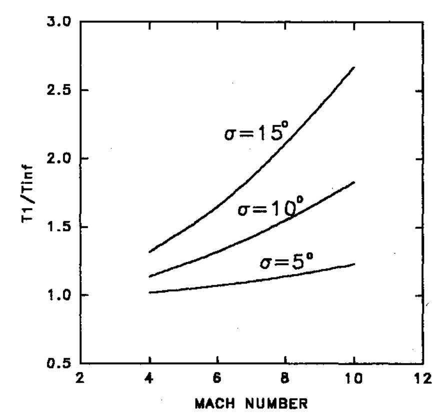

Fig. 14 Temperature ratio across conical shock for cones of several half-angles.

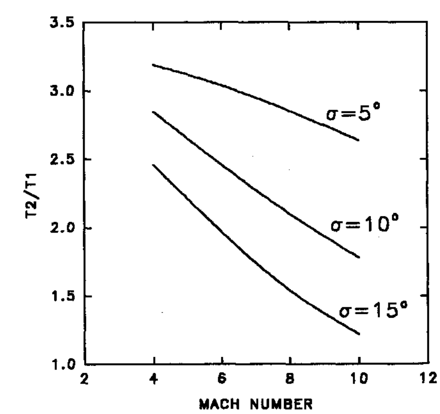

Fig. 15 Minimum temperature ratio across jet bow shock required for ignition for cones of several half-angles.

most restrictive set of conditions. At the lower Mach number, the region in which combustion is expected, extends a distance outward from the surface equal to about 20% of the projectile radius. At $M = 11$, this number grows to 38 and 58% of the radius, depending on the cone angle. This is to be compared with the typical projectile-to-barrel distance of 20–25% of the radius, not all of which is affected by combustion.

Lastly, the practical concerns associated with the jet gas confinement requirement must be addressed. Specifically, the parameters of interest are the required stagnation pressure, volume, and mass of the stored gas. The criteria used for choosing the needed reservoir stagnation pressure is the need to maintain choked flow at the jet nozzle and to achieve the needed penetration into the freestream. Basic theory requires that the ratio of the jet stagnation pressure to external static pressure (Poj/Pe) be at least 1.89. The external pressure at the jet exit port should be related to the surface pressure within the small separated region upstream of the jet, and not to the pressure directly downstream of the shock. The high shock pressure is not felt at the surface because of the subsonic separated flow region. This is shown in the computed pressure plots in Ref. 7. The required jet stagnation pressure can be expected to increase with the external Mach number. Therefore, the pressure must be chosen based on the highest Mach number expected. Choosing $M = 10$ as an example, Poj will have to be at least 113 atm for the fill pressure of 10 atm in order to maintain sonic outflow. The operational ram accelerators often require higher fill pressures. Assuming a fill pressure of 50 atm used in the recent ARL tests, the minimum jet stagnation pressure would have to be about 570 atm. To achieve meaningful penetration height, the actual stagnation pressures will have to be much higher. However, it must be remembered that the ARL tests were conducted at much lower Mach numbers and with less energetic fuel oxidizer mixture. It is, therefore, possible that lower fill pressures will be sufficient for some applications, especially for the ram accelerator stages where Mach number is high.

The amount of gas necessary is a function of many variables. The system-related variables translate basically into the time the projectile requires to traverse the accelerator. It is reasonable that for the system discussed here the required mass will be on the order of 100 g. The volume required to store 100 g of oxygen at 500-atm pressure is about 150 cc. Within the same volume, 200 g of the gas could be contained at 1000 atm. This could be easily accommodated in a 91.5-mm-diam projectile and the mass would be insignificant compared to the projectile mass of 4.5 kg. The containment vessel would probably cause a greater design problem.

A question may reasonably be asked whether a significant projectile acceleration can take place within the assumed time and mass constraints. Further assuming a detonative process and the normalized heat of reaction value of 20 for the stoichiometric hydrogen–oxygen mixture, the pressure ratio across the reaction region would be about 18 for the C–J process and up to 40–100 for overdriven detonation at Mach 6–10. Since the shock wave under consideration is curved (normal at the surface), the C–J value marks the limit for the detonative process. Overdriven detonation can take place along the segment of the shock wave below this point. Assuming a small afterbody angle so that most of the high pressure behind the detonation wave be available for thrust, the velocity increment during the 0.01-s time span could be 590 m/s for the pressure ratio of 40 and 1030 m/s for the average value of 70; this, using 10-atm fill pressure. It is clear that increasing the fill pressure or the acceleration duration (more gas needed) would increase these numbers proportionally.

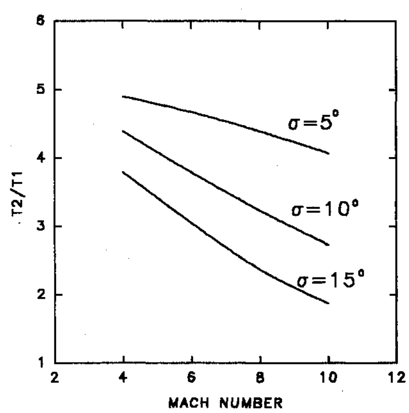

Fig. 16 Maximum temperature ratio across jet bow shock required for ignition for cones of several half-angles.

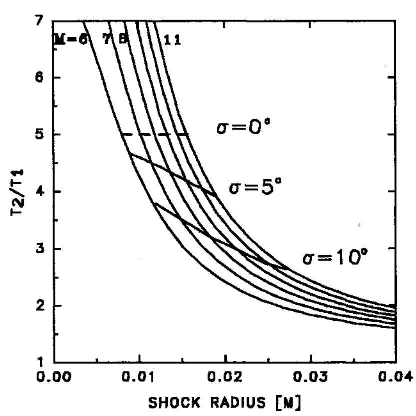

Fig. 17 Maximum temperature ratio across jet bow shock required for ignition for cones of several half-angles overlaid on shock temperature ratio plots for various Mach numbers. Injection rate is 1.54 kg/s, O_2 into $2H_2 + O_2$ at 10 atm.

Extension of Applicability

The concepts presented in this article may well lend themselves to an external detonative propulsion system for use on large vehicles (rockets, satellite launch vehicles, or hypersonic transport). Such a propulsion system has been suggested by a number of researchers. The feasibility of such a system depends on the injection and mixing of fuel with ambient air over the forebody of the vehicle and its subsequent ignition. Since the problem of mixing at hypersonic speeds is severe a vehicle of large length will be required.

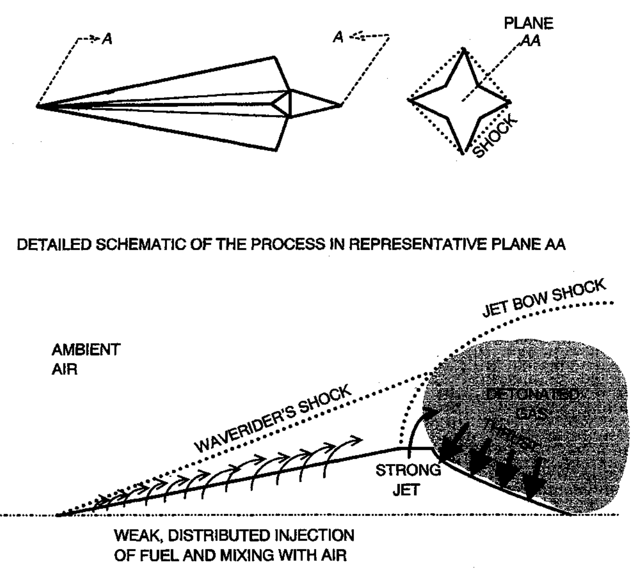

Fig. 18 Application of the present concept to hypersonic propulsion within the atmosphere. Vehicle's nose is a waverider, while the aftbody receives the thrust.

Figure 18 is a schematic illustration of the proposed jet interaction system applied to a long, hypersonic configuration. The vehicle's nose is of a star cross section, and the shape used is designed to produce a waverider with a four-fold symmetry. Star cross sections have long been known for their optimal drag characteristics. The symmetry offers equal maneuvering capability in all directions. The planar shock wave attached to the leading edges of the configuration heats and compresses the fluid between the shock and the body surface. Fuel (most likely hydrogen) is injected through relatively weak jets distributed over the forward portion of the body and are allowed to mix with ambient air, as shown in Fig. 18. On the shoulder portion of the body, final, strong jets are located that impart enough heat and compress the mixture sufficiently, via the resulting shock wave, to promote reaction. The thrust force will be obtained on the inward tapered portion of the projectile. It is also conceivable that the strength of the final jets may be controlled, to maneuver the configuration.

Conclusions

A new hybrid approach to the ram accelerator system utilizing an active projectile was presented and discussed. The principle of jet interaction was introduced for triggering and enhancing the chemical reaction, either combustion or detonation, in a reactive gas mixture. In the proposed method the projectile carries internally a small amount (in proportion to its mass) of gas at very high pressure, that is released continuously into the combustible environment during the acceleration process, through a number of jet nozzles distributed circumferentially around the projectile's midsection. The bow shock produced by the jets heats and compresses the ambient gas mixture sufficiently for the reaction to take place. At the same time, the released gas, which may be fuel, oxidizer, or inert, has the ability to alter the ambient mixture downstream in such a way as to make it more energetic, thus enhancing the reaction process. The present method is applicable to the various modes of propulsion proposed for the barrel-dependent ram accelerator. However, only the supersonic combustion modes (coupled and decoupled) are applicable to the external propulsion (barrel-independent) configuration. The calculated results show that it is possible to ignite the combustible mixture in passage through the bow shock caused by the jet. It is possible to promote reaction up to a distance from the body similar to its radius. For the projectile masses in the range of kilograms having a radius of 46 mm, the required amount of gas needed would be on the order of 100 g. The required chamber pressure for the gas storage system would be high, but the required storage volume would be within limits easily accommodated by a projectile of the previous dimensions. 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. The reaction front can be envisioned as being anchored to the jet, that acts as a flameholder. Therefore, even in application of the present method to the established, tube-interactive mode, the present method has an advantage of rendering the projectile design less Mach number dependent. After the projectile has exited the accelerator, the use of jets for vehicle control is a very attractive choice. Detailed numerical investigation followed by experiments will be necessary to develop this concept further.

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