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Abstract

The effect of confinement on the initiation of detonation waves by supersonic projectiles is investigated. For experiments in a large diameter detonation chamber, the projectile bow shock cannot reach the tube wall during the experimental test time, making the experiment effectively unconfined. In this case, a projectile is capable of direct initiation only, wherein the combustion sufficiently couples to the projectile bow shock to propagate as a free-running detonation. If the dimensions of the detonation chamber are reduced to the order of the projectile diameter, multiple bow shock reflections and boundary layer growth can promote ignition and the confinement of the chamber wall can assist in the initiation of detonation via deflagration to detonation transition (DDT) mechanisms. This paper reports an experimental examination into the effect of confinement. Spheres with a diameter of 1.27 cm were fired into a stoichiometric mixture of hydrogen and oxygen diluted with argon. The mixture was contained in a tube 3.81 cm in diameter. Combustion waves were observed to form in the wake of the sphere and eventually overtake the sphere. This result is in contrast with prior experiments in an 18 cm diameter detonation chamber with the same mixture and sphere size. In the large chamber, only direct initiation from the sphere itself was observed. The results indicate that initiation in a confined environment can be realized under a much wider range of conditions (lower projectile Mach numbers and mixture pressures) than in an unconfined environment. The relevance of this result to the ram accelerator hypervelocity launcher concept is demonstrated by reproducing similar wake-ignition phenomenon with a projectile in a standard propellant mixture. The effect of confinement is shown to play an important role in the initiation and stabilization of combustion in the ram accelerator.

1. Introduction

A large body of work exists on the problem of projectiles traveling at supersonic speeds in combustible gas. Beginning with Zeldovich and Leipunsky in the 1940's, the problem of combustion and detonation induced by the strong bow shock of a blunt projectile has been extensively investigated.[1] In the 1960's, several researchers studied the interesting flow pulsations observed behind the bow shock of blunt projectiles in combustible gas.[2–6] The steady flow field of combustible gas around conical, spherical, and other bodies of revolution was analyzed theoretically by Chernyi and others.[7–10] In the 1990's, numerous numerical simulations returned to the oscillatory phenomenon observed in the 1960's and were able to reproduce the pulsating flow fields computationally. The work of Matsuo and Fujiwara[11–15] and Wilson and Sussman[16–18] are particularly noteworthy in their further elucidation of the mechanism of this instability. Recent experiments using a flow of combustible gas over stationary models has allowed more sophisticated flow visualization techniques to be applied to this problem.[19,20] Kaneshige and Shepherd[21] and Higgins and Bruckner[22] initiated renewed experimental investigations to examine the initiation of detonation by blunt projectiles. The latter work largely validated a theory published independently by Lee[23] and Vasiljev[24] for the initiation of detonation by supersonic projectiles. Thus, a complete picture of the interaction between projectiles and combustible media is beginning to form.

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The 1980's and 1990's also marked the emergence of a hypervelocity launcher concept called the "ram accelerator," wherein a sharp-nosed projectile is fired at supersonic speeds from a conventional gun into a tube filled with combustible gas.[25,26] The projectile is smaller in diameter than the tube, so that as it travels down the tube, the combustible gases are compressed around the projectile by an oblique shock system and burned behind the projectile. The resulting high pressure region stabilized on the projectile base generates thrust which drives the projectile down the tube at very high accelerations (tens of thousands of g's). The ram accelerator is usually operated with the projectile at speeds below or nearly equal to the Chapman–Jouguet speed of the mixture through which it travels. In this "thermally choked" mode, the combustion mechanism is not believed to be a detonative process and is instead more similar to the dump combustor of a conventional ramjet.[26] In the largely unexplored superdetonative regime, the propulsive mode may, or may not, depend on the initiation and stabilization an of oblique detonation on the projectile.[27] An alternative mechanism for combustion in the superdetonative mode is shock-induced combustion, in which the energy release is not intimately coupled with the initiating shock wave. To date, the exact details of combustion processes in the ram accelerator have not been fully elucidated. The determination of successful operation of the device is almost exclusively based on the observed acceleration of the projectile.

Development of the ram accelerator has occurred independent of the prior body of work on projectiles in combustible gases discussed above. A number of important differences account for this. For one, the ram accelerator is operated with high pressure propellants (tens of bar initial pressure) which are formulated very rich with insensitive fuels (methane) and heavily diluted with inert gases (nitrogen, helium, etc.). The experiments on projectiles in combustible gases in the 1960's (and the contemporary computation simulations of those experiments) used more readily detonable mixtures with stoichiometric or near-stoiciometric mixtures at pressures of one bar or less. The ram accelerator projectile is a complex shape, with a sharp nose cone for efficient compression of the incoming flow, fins for stabilizing the projectile in-tube, and a truncated conical body for stabilizing the combustion process. Basic experiments on projectiles in combustible gas used simple, axisymmetric shapes (spheres, cones, etc.) which were blunt in comparison to a typical ram accelerator projectile. Finally, the ram accelerator operates in a tube, with a significant degree of confinement. The ram accelerator projectile is typically on the order of 50% of the tube cross sectional area. All prior experiments examining the basic physics of projectiles in combustible gases were performed in large chambers where no significant interaction between the projectile and the chamber wall occurred. These important differences have meant that the research on flow fields around projectiles in combustible gases have offered little, if any, insight into the operation of ram accelerators. The mechanism and stabilization of the combustion processes in the ram accelerator remain opaque.

Recently, variations on the ram accelerator, such as the "external propulsion accelerator," have appeared which do not involve interaction with the tube wall.[29] This concept bears a greater resemblance to experiments with projectiles in combustible gases performed in the 1960's. In connection with this concept, analyses have appeared which attempt to estimate the capabilities of the ram accelerator and the external propulsion accelerator.[23,29] For example, the external propulsion accelerator requires a blunt, forward-facing step to initiate combustion. The resulting drag from this step offsets the thrust communicated to the projectile by combustion, but this drag is essential to initiate the combustion process.

In the confined ram accelerator, the role of projectile drag in initiating combustion has not been investigated. The traditional view of the ram accelerator is that combustion is initiated and stabilized by the multiple shock reflections between the projectile and tube wall or in the recirculation zone behind the blunt base. In fact, the performance of the thermally choked ram accelerator can be shown to be completely independent of projectile drag.[30] Lee[23] has noted, however, that in the experiments of Benedick[31] the initiation of detonation by steel plates launched explosively into combustible gas occurred both on the plate itself and where the bow shock reflected from the "floor" of the

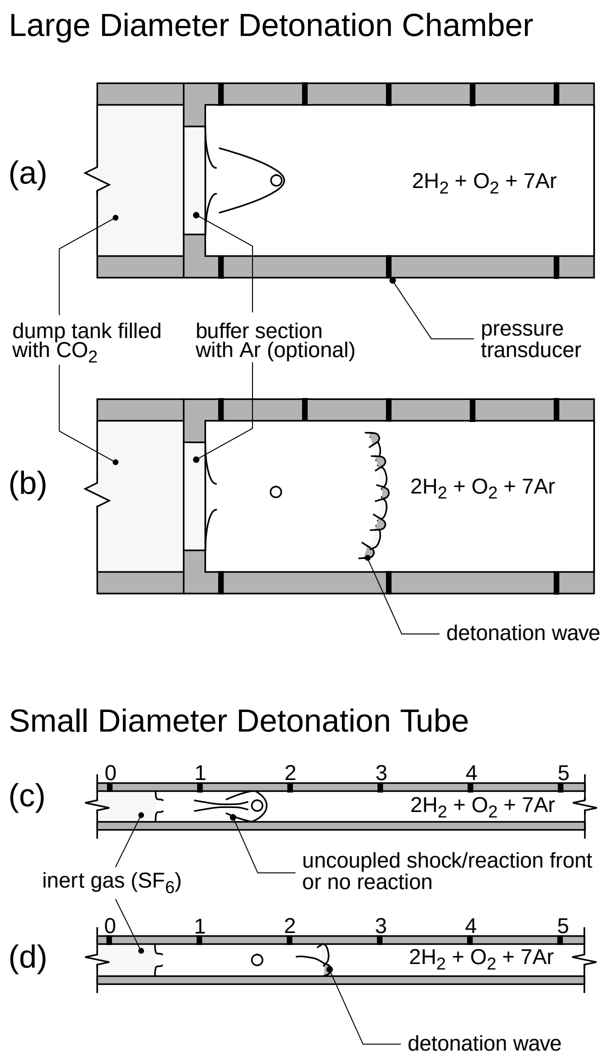

Fig. 1 Schematic of detonation initiation by blunt projectiles:
(a,b) Direct initiation in an unconfined environment.
(c,d) Initiation in a confined tube.

experiment. This result suggests that the requirements for initiation, i.e., projectile drag, may be similar even when interaction with confinement is present.

The current work is an attempt to bridge the gap between the basic research on projectiles in combustible gases and the ram accelerator. The particular issue addressed here is the confining effect of the tube on the initiation of detonation by projectiles. The basic phenomenon under investigation is illustrated schematically in Fig. 1. A blunt projectile fired at supersonic speeds into a large chamber of combustible gas, as shown in Fig. 1a, is typical of experiments examining combustible flow fields in that the bow shock does not reflect from the chamber walls during the experiment. A possible outcome of such an experiment, the initiation of a free running detonation wave, is illustrated in Fig. 1b. Here, the detonation outpaces the projectile, since the projectile is traveling below the detonation speed. This mode of initiation is "direct," in that the bow shock directly transitions to a detonation, just as the decaying blast wave transitions to detonation in more conventional detonation experiments using exploding wires, blasting caps, etc.[32] Alternative outcomes of this type of experiment are combustion occurring downstream of the bow shock or oscillating flow fields where the combustion is weakly coupled to the bow shock. A detailed experimental investigation of the boundary between these unsteady/detonation and steady/periodic regimes is reviewed in Section 2 below.

In Fig. 1c, a projectile is fired into a tube with internal diameter larger than, but on the order of, the sphere's diameter. The bow shock of the sphere now immediately reflects off the tube wall, intimately coupling the flow field with the confining effects of the tube. Of course, under the conditions in which detonation would be observed in an unconfined environment (Fig. 1b), initiation will also occur in the confined tube. Several additional factors, however, contribute to ignition in the confined case which would not be observed in the unconfined case, such as the long train of oblique shocks which reflect back and forth across the tube behind the projectile. These effects increase the residence time of a fluid element in the heated regions of the flow field. Once ignition occurs, the confinement of the tube also allows mechanisms of detonation initiation, such as deflagration to detonation transition (DDT), to occur which are not otherwise observed in unconfined experiments.[33,34]

Finally, the issue of whether the results with a blunt projectile in a confined tube has any relation to the ram accelerator is addressed in Section 4. This section discusses experiments in which a typical ram accelerator projectile is fired into a standard propellant mixture. Unlike conventional ram accelerator experiments, however, the projectile enters from an inert gas without the combustion wave already stabilized on the projectile. Thus, the experiment is similar to that shown in Fig. 1c,d, only with the sphere replaced by a projectile and the detonable gas mixture replaced with a propellant mixture capable of supporting ram acceleration. Thus, the effects of changing the confinement, projectile geometry, and propellant mixture are demonstrated, underscoring the important differences between prior experiments in combustible gases and the ram accelerator.

2. Results without Confinement

Experiments investigating the critical conditions for detonation initiation by blunt projectiles are reported in Refs. 22 and 35. The results of this investigation are reviewed briefly here; complete details can be found in the references cited. The basic experiment consisted of firing a chrome steel sphere from a single-stage gas gun into a chamber filled with a detonable mixture of stoiciometric hydrogen and oxygen diluted with 70% argon ($2H_2$+O_2+7Ar). The sphere was launched from the gas gun using a sabot. Discarding the sabot necessitated having a large tank of low pressure inert gas (carbon dioxide) between the gas gun and the detonation chamber. Hence, a steady, supersonic flow field was established around the sphere in an inert environment before it entered the combustible gas (see Fig. 1a). The outcome of an experiment was monitored via pressure transducers mounted on the chamber wall. The large diameter of the chamber (18 cm) compared to the sphere diameter (1.27 cm) ensured that interaction between the bow shock and the chamber wall did not account for any observed detonations.

In experiments with the detonation chamber, the pressure transducers recorded either a weak, nonreacting bow shock propagating at the sphere speed or a free running detonation propagating at the CJ speed. Hence, the distinction between a projectile initiated detonation and no detonation remained distinct and well defined. In some experiments near the critical pressure when the sphere was at approximately the CJ speed, a “delayed” initiation was observed, wherein the sphere would travel for 10 cm or more before detonation was initiated. Even in these experiments,

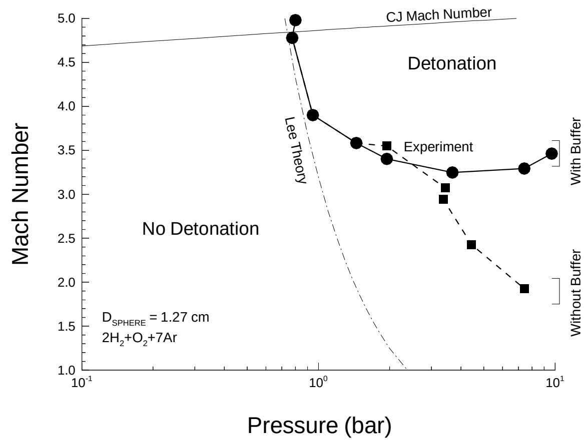

Fig. 2 Results from firing spheres into a large diameter detonation chamber.

however, the initial bow shock appeared identical to a nonreacting flow until the onset of detonation occurred. All observed initiations occurred in the immediate vicinity of the sphere. The results of these experiments are shown in Fig. 2.[35] Here, the Mach number of the sphere required to initiated a detonation is plotted as a function of the mixture initial pressure. The sphere was always at a velocity below or approximately equal to the CJ detonation velocity (the nearly horizontal line in Fig. 2). Of course, when detonations were initiated, the resulting wave propagated at very nearly the CJ speed, regardless of the sphere’s initial speed. The sphere was able to initiate a detonation provided the sphere Mach number was greater than approximately Mach 3.4 and the mixture pressure was greater than approximately 1 bar. This region forms a quadrant labeled “Detonation” in Fig. 2.

The results of the experiments in Fig. 2 were found to be sensitive to the details of how the sphere entered the combustible mixture. If a buffer of inert gas (argon) was located between the main diaphragm at the entrance to the chamber and the combustible gas, the critical Mach number was observed to be between Mach 3.2 and Mach 3.4 for fill pressures between 1 and 10 bar. If the sphere transitioned directly from the low pressure (0.17 bar) carbon dioxide used to strip the sabot to the combustible mixture, the critical Mach number was found to decrease as the mixture pressure increased, giving a critical Mach number of less than Mach 2 at 7.5 bar fill pressure. The difference between the results with and without a buffer of inert gas between the main diaphragm and the combustible gas is believed to be the result of unsteady shocks generated when the sphere penetrated the diaphragm.[35,36] At lower pressures and higher Mach numbers (near the CJ Mach number), no difference in results is observed with the different diaphragm techniques.

The predictions of a simple theory due to Lee[23] which specifies the critical boundary between detonation and no detonation is also shown in Fig. 2. This theory equates the critical energy required to initiate a cylindrical detonation with the energy deposited in the flow by the sphere. The critical energy per unit length for a cylindrical detonation is given as[23]

$$E = 10.07 \gamma p M_{CJ}^2 \lambda^2 \tag{1}$$

where λ is cell size and p is the mixture initial pressure. By the hypersonic blast wave analogy, the energy deposited into the flow by the projectile is equal to the drag on the projectile itself

$$D = \frac{1}{2} \rho V_{sph}^2 A C_D \tag{2}$$

Where the drag coefficient has a value of $C_D \approx 1$ for a sphere. Equating Eqs. (1) and (2) and solving for the required projectile Mach number yields

$$\frac{M_{sph}}{M_{CJ}} = 5.07 \frac{\lambda}{d_{sph}} \tag{3}$$

This equation agrees with the analysis of Vasiljev, except for the numerical constant.[24] This relation is plotting in Fig. 2, where the cell size measurements of Barthel[37] are used to relate the mixture pressure to the cell size required in Eq. (3). The theory is in remarkably good agreement with the experimental results, down to a Mach number of approximately 3.4. This Mach number is postulated to be an autoignition limit[36] below which the bow shock does not raise the gas temperature sufficiently to initiate chemical reactions. Thus, the requirements for detonation initiation are: (i) a critical energy deposition (drag) and (ii) a shock wave of sufficient strength to heat the gas above the autoignition limit. The Lee–Vasiljev theory was further validated by varying the sphere size from 0.5 to 2.5 cm. The resulting critical mixture pressure was observed to be in excellent agreement with Eq. (3) given above.[35]

3. Experiments with Confinement

Experimental Procedure

To examine the effect of tube confinement, experiments similar to those discussed in Section 2 were performed in a small diameter tube (3.81 cm). The sphere diameter was kept constant at 1.27 cm. Thus, the sphere was one third the tube diameter, representing an occlusion of 11% of the tube cross-sectional area. Because of the similarity of these experiments to those in Section 2, the complete experimental set-up will not be provided here; the details can be found in Ref. 35. However, the fact that the experiments now involve a small diameter tube, as opposed to a large diameter chamber, introduces a few additional challenges in implementation. Namely, the requirement of stripping the sabot in-tube, without the use of a large dump tank between the gas gun and the test section, necessitates modifying the sabot discard technique. Also, the fact that the sphere now interacts with the tube introduces an additional parameter to the experiment which must be measured: the location of the sphere with respect to the tube axis. This section discusses the details of the experiment.

The discard of the sabot is accomplished using a gas dynamic technique. For the experiments in Section 2, the sphere/sabot combination was injected from the gas gun into a tube containing carbon dioxide at low pressure (0.17 bar). The resultant normal shock caused by the impact of the sabot created a high pressure on the sabot face, rapidly decelerating it. The sphere, nearly at rest with respect to the shocked gas between sabot face and the normal shock, experienced almost no drag. After 6.75 m of travel, the normal shock expanded from the tube into a large dump tank and quickly decayed to an acoustic. The sphere passed through this decaying wave into free, supersonic flight before entering the chamber of combustible gas.

For experiments with confinement, the sabot/sphere acceleration, sabot discard, and

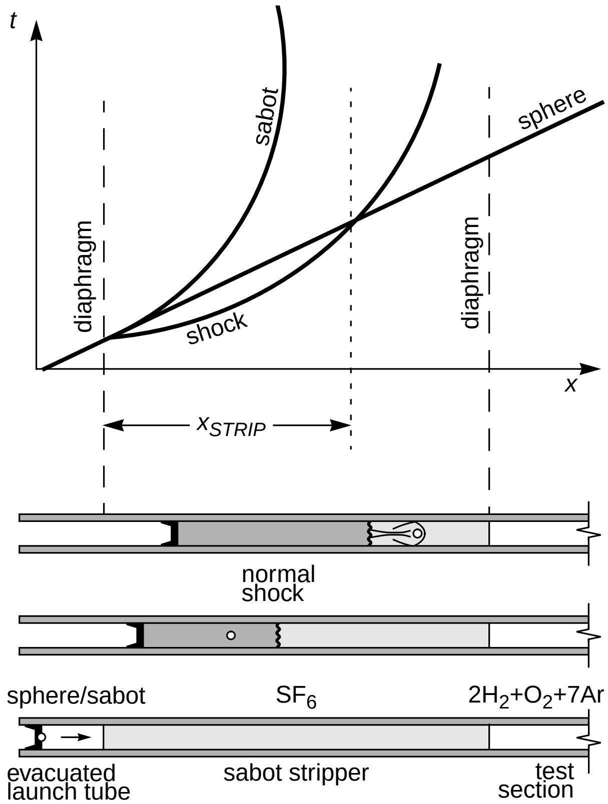

Fig. 3 *x–t* diagram of the sabot stripping process.

experiment in combustible gas are accomplished in a single, 3.81 cm diameter tube. The sabot is still discarded gas dynamically, but now without the use of a large dump tank to "swallow" the strong shock wave generated by the sabot impacting the inert gas. The entire stripping operation must be accomplished in-tube. This process is shown in Fig. 3. The sabot impacts the inert gas and generates a strong shock wave, whose strength is given by[38]

$$\frac{u_p}{a_0} = \frac{2}{\gamma - 1}\frac{M_s^2 - 1}{M_s} \tag{4}$$

where M_s is the shock Mach number, u_p is the sabot velocity at impact, and a_0 is the initial sound speed of the inert gas used for sabot stripping. The high pressure generated by the normal shock causes the sabot to decelerate while the sphere continues on at nearly a constant velocity (straight line trajectory in the *x–t* diagram). As the sabot decelerates, it sends rarefactions into the shocked gas which overtake the normal shock and weaken it. As the shock weakens, it decelerates and eventually the sphere emerges from the shock after traveling a distance x_{strip}, the shock stripping distance. The sphere at this point is in supersonic flight and experiences significant drag. Simply having the sphere in front of the normal shock, however, is not a sufficient requirement before the sphere can be injected into the combustible section of tube, because the normal shock may initiate a detonation in the combustible mixture which would not otherwise be observed. Such a detonation would overtake the sphere, thus confusing the results. Hence, it is necessary for the sphere to sufficiently outdistance the normal shock before it is allowed to enter the combustible gas. In the experiments reported in this paper, the sabot stripper stage was of sufficient length to ensure that the sphere exited the 2-m-long test section (thus ending the meaningful test time) before the normal shock from the sabot stripping process entered the test section.

In these experiments, sulfur hexaflouride (SF_6) was used as the inert gas to accomplish the sabot stripping. In this dense, high molecular weight gas, the initial shock Mach number for a given sabot velocity is very large in comparison to that obtained in more typical gases (nitrogen, carbon dioxide, etc.). The higher shock Mach number, however, generates a greater pressure on the sabot face, increasing the sabot's deceleration and resulting in a more rapid decay of the normal shock. Hence, the sphere emerges from the decaying normal shock quickly, within a few meters of travel. Ironically, the use of helium would generate a relatively weak shock of low Mach number, but the shock would not decay as quickly and the shock stripping distance would be on the order of hundreds of meters! While this distance can be reduced by increasing the initial pressure of the inert gas, the high pressure causes increased sphere deceleration when the sphere is in free supersonic flight in front of the normal shock. Also, if the inert stripper gas is at a higher pressure than the test section pressure, the inert gas will act as the driver of a shock tube and send a strong normal shock into the test section when the sphere punctures the diaphragm between sabot stripper and test section. For the experiments reported here, the test section pressure was as low as 0.25 bar, limiting the sabot stripper pressure to a value less than 0.25 bar. Hence, the use of a high molecular

Table 1: Results with Confinement

Test Section Pressure (bar)	Sabot Stripper Pressure (bar)	Mach (No Det.)	Mach (Det.)
0.25	0.18	3.36	3.55
0.45	0.35	3.01	3.15
0.95	0.85	2.33	2.55
3.44	0.85	1.73	2.05

weight gas with a low ratio of specific heats ($\gamma \sim 1.1$ for SF_6) was essential to realize in-tube sabot stripping. The length of the sabot stripping stage in all experiments was 8 m. The pressure of the sabot stripper for different test section pressures is given in Table 1. The fact that the sabot stripper is at a lower pressure than the test section does not contaminate the results, since the projectile will quickly outrun any rarefactions generated by the expansion of combustible gas into the sabot stripper section.

The projectile velocity is measured by tracking the bow shock reflection off the tube wall as recorded by pressure transducers. Unfortunately, this technique is not as accurate as electromagnetic (EM) techniques used to measure the velocity of the sabot and ram accelerator projectiles, both of which carry magnets on board. This technique can only measure the passage of the sphere with 5 μs accuracy (as compared to 1 μs accuracy for the EM technique), so the velocity measurements reported here have an uncertainty of approximately 25 m/s.

For the results reported in Section 2, an experiment was specified entirely by the diameter and velocity of the sphere and the mixture composition and pressure. When the effect of confinement is introduced, additional parameters are required to specify the experiment, namely the degree of confinement and the position of the sphere with respect to the tube axis. The degree of confinement (ratio of sphere to tube diameter) was fixed at 0.33 for the experiments. Unfortunately, the position of the sphere as it travels down the tube could not be fixed. While ideally it would remain on the tube axis, resulting in an axisymmetric flow field, in practice the sphere was not perfectly centered. While the sphere was held in position at the center of the sabot by a hemispherical cavity, any number of factors (separation from the sabot, diaphragm impact, flow field asymmetries, etc.) could have resulted in a small tangential velocity which, over the 8 m length of the sabot discard process, would have resulted in the sphere being off-axis. If the sphere is off center, the bow shock is stronger as it reflects off the near wall and weaker as it reflects off the far wall. This sets up an asymmetry which will be repeated as the oblique shocks reflect back and forth across the tube. The effect this asymmetry has on the initiation of detonation is not known and is difficult to quantify. The experiments in this study proceeded on the assumption that the asymmetry is a higher order effect compared to the mixture pressure and sphere velocity. The position of the sphere was recorded, however, at a point in the sabot stripper stage after it had emerged from the normal shock, 2 m before entering the test section of combustible gas. A ring of 8 pressure transducers, spaced at 45 , recorded the arrival time of the bow shock. The maximum difference in arrival time specified the direction and magnitude of displacement of the sphere from the tube axis. Using an empirical correlation of bow shock shapes due to Billig,[39,40] the position of the sphere could be computed. This technique was originally developed by Hinkey et al.[41] for determining the degree of translation and canting of ram accelerator projectiles. Determining the displacement of the sphere is considerably simpler because it is perfectly symmetrical and can only translate.

The combustible mixture in the test section is contained with a thin (5 mil) Mylar diaphragm. The mixture is prepared by flowing the constituent gases (hydrogen, oxygen, and argon) simultaneously through separate choked orifices. The gases are combined downstream of the orifice and injected into the tube through a single fill line. The gas is allow an additional half hour mixing time once in the tube. The mixture pressure was varied between 0.25 bar and 3.4 bar. The results of the experiment in the test section are monitored with piezoelectric pressure transducers and luminosity sensors. These instruments are spaced 40 cm apart, beginning 20 cm after the diaphragm which separates the sabot stripper from the test section.

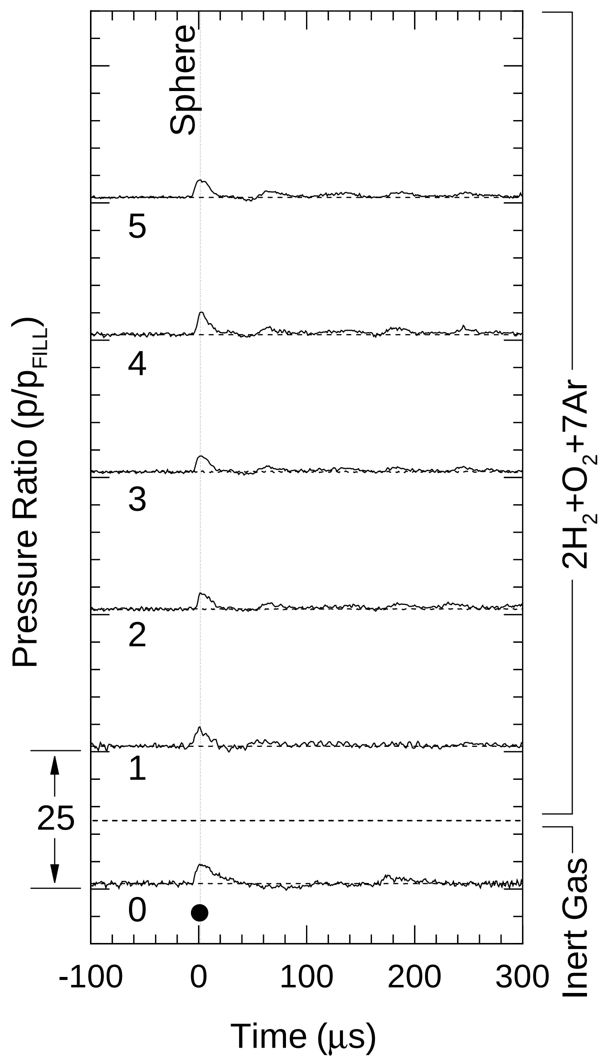

Fig. 4a Pressure (solid line) and luminosity (dashed line) data for a sphere traveling at 800 m/s (47% CJ speed).

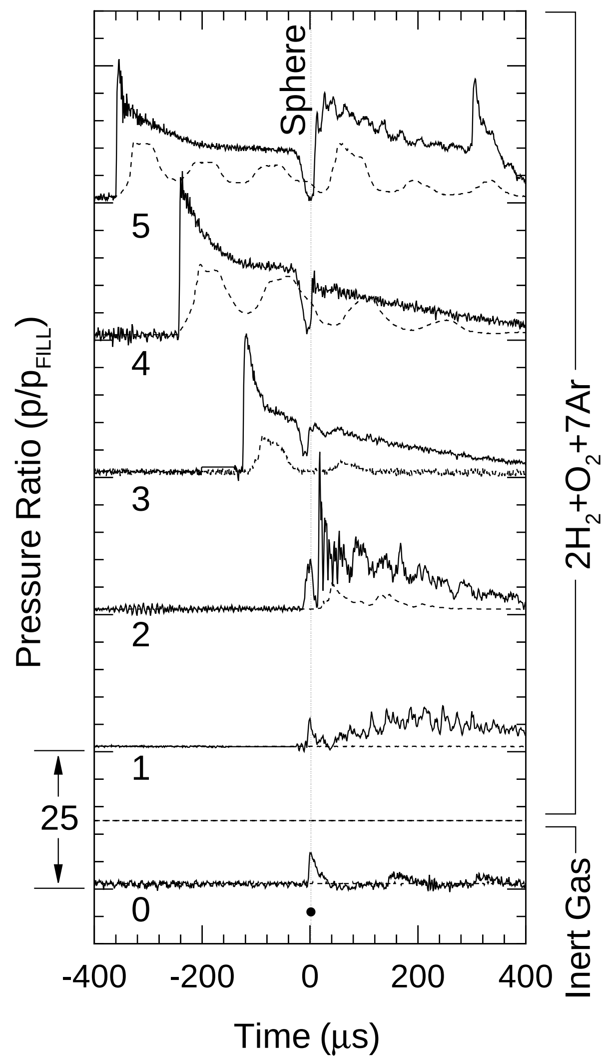

Fig. 4b Pressure (solid line) and luminosity (dashed line) data for a sphere traveling at 1100 m/s (65% CJ speed).

Results

The results of firing a 1.27 cm sphere into a 3.81 cm diameter tube containing a mixture of $2H_2$+O_2+7Ar at 1 bar are shown in Fig. 4. The pressure and luminosity traces are synchronized with the passage of the sphere (defined to be $t = 0$ for each trace). The position of each transducer is shown in Fig. 1c. The pressure data is normalized by the fill pressure, while the luminosity data is only qualitative and left unscaled. A silhouette of a sphere is also shown, scaled by its velocity. In Fig. 4a, the sphere is traveling at 800 m/s (Mach 2.3) or about 47% of the theoretical CJ speed. The first pressure trace (trace 0) is taken from the SF_6 sabot stripping gas. The pressure pulse with amplitude of approximately 5 times the fill pressure is the result of the bow shock reflecting off the tube wall. As the sphere enters the combustible mixture, no noticeable change in wave activity around or behind the sphere is observed. No detonation initiation was observed, and the complete lack of luminosity suggests that there was no combustion.

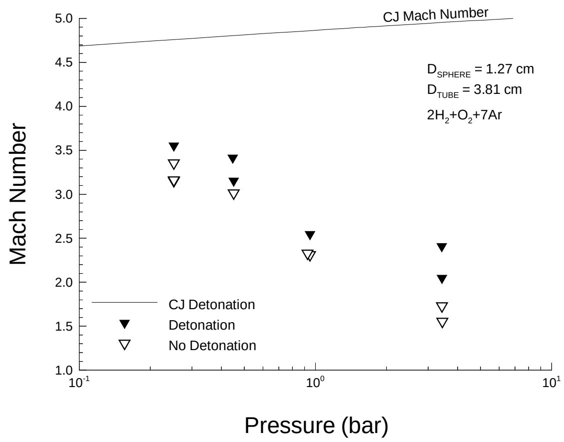

Fig. 5 Results from firing spheres into a small diameter detonation tube.

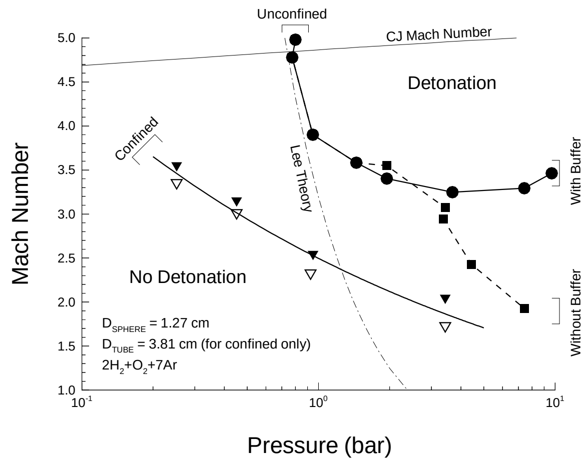

Fig. 6 Comparison of detonation by projectiles in confined and unconfined experiments.

In Fig. 4b, the sphere velocity has been increased to 1100 m/s (Mach 3.1) or about 65% of the theoretical CJ speed. The first trace is again from the inert, sabot stripping gas (SF_6). The next traces (1–5) are from the combustible mixture. In trace 1, an increase in pressure, presumably from combustion, is observed to occur 100 to 200 µs after the passage of the projectile. The wave activity around the sphere itself, however, is unchanged. In trace 2, the combustion wave behind the projectile has steepened into a strong shock and luminosity is observed behind the wave. By trace 3, this wave has overtaken the sphere and from 3 to 5 propagates at 1680 m/s, within 1% of the theoretical CJ detonation velocity. This is clearly an instance of a detonation initiated by a supersonic projectile traveling through a combustible mixture. The critical velocity of initiation is between 800 m/s and 1100 m/s. Further experiments narrowed this critical velocity down to a range of 840 40 m/s.

The results of the experiments in Fig. 4 and similar experiments in the same mixture at different initial pressures are shown in Fig. 5. The instance of a successful initiation are denoted with a solid symbol; no initiation is marked by a hollow symbol. In all cases of successful initiation, the initiation event was observed to follow the pattern of Fig. 4b: ignition in the wake, leading to a combustion wave which would overtake the sphere after approximately 1 m of travel. As the mixture pressure decreased, the velocity required to initiate detonation increased, following the same qualitative trends as the unconfined results in Section 2.

A quantitative comparison of the results with and without confinement are shown in Fig. 6. Here, only the critical points from Fig. 5 are reproduced, along with the unconfined results from Fig. 2. A curve is fit between the critical points for the results with confinement, separating the region of "detonation" from "no detonation." Figure 5 shows that confinement allows the sphere to initiate detonation under a wider set of conditions than is possible with an unconfined experiment. Specifically, the sphere is able to initiate detonation at Mach numbers as low as Mach 2 and at pressures as low as 0.25 bar, while in unconfined experiments the sphere Mach number is required to be greater than Mach 3.2 (when an inert buffer was used between the main diaphragm and the combustible mixture) and the mixture pressure must be greater than 1 bar.

The displacements of the center of the sphere from the tube axis estimated from the difference in arrival time of the bow shock is shown in Fig. 7 for the experiments shown in Fig. 5. The same symbol convention is used: solid for detonation, hollow for no detonation. The uncertainty in this technique of computing sphere position is estimated to be 1 mm for the magnitude of radial displacement and 25 for the direction of displacement. Fig. 7 can be thought of as a "witness plate" located ahead of

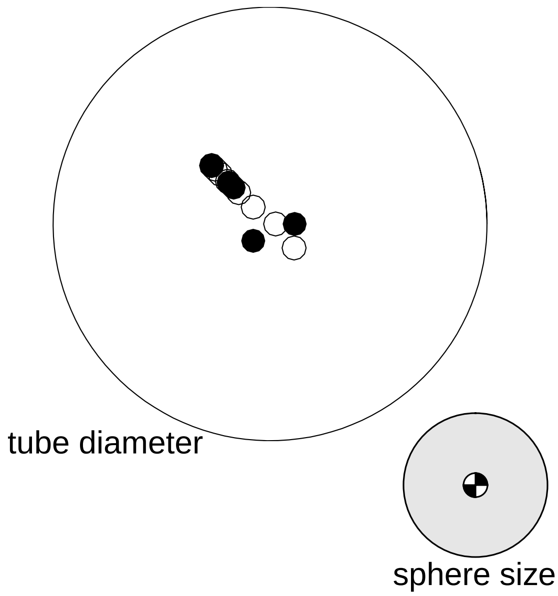

Fig. 7 Position of the center of each sphere in the tube for the experiments in Fig. 5.

the test section that recorded the trajectory of the center of the sphere. Notice that sphere displacements from the center line were as great as 7 mm (roughly one sphere radius). No correlation, however, between “detonation” and “no detonation” results can be made with the sphere’s position. This result confirms the initial assumption of these experiments: that the outcome is dictated primarily by the velocity of the sphere and the mixture fill pressure. The position of the sphere as it travels down the tube has an unquantified, but apparently higher order, effect on initiation.

4. Relevance to the Ram Accelerator

The results of the prior section demonstrated that ignition and transition to detonation may occur in the wake of a projectile in a confined tube. Since the ram accelerator operates in a confined tube, this mechanism may be expected to play an important role here as well. The results in Fig. 4b, however, show a combustion wave which transiently sweeps over the sphere, communicating little thrust to the sphere. Thus, the relevance of this phenomenon to the combustion waves observed to travel with ram accelerator projectiles is unclear.

Several important distinctions exist between the experiments with confinement in Section 3 and the ram accelerator. For one, the mixture used in Section 3 ($2H_2+O_2+7Ar$) is very sensitive; it may well be impossible to stabilize ram accelerator operation in such a reactive and easily detonated mixture. Additionally, the projectile used in Section 3 (a sphere) is a shape not conducive to stabilizing the combustion process on the projectile. A sharp nose cone to efficiently compress the flow and a conical base to contain the combustion wave behind the projectile are necessary to realize successful ram accelerator operation and prevent the “unstart” phenomenon. Finally, fins which span the distance between the projectile body and the tube wall are required to keep the projectile centered on the tube axis. In this section an experiment similar to those in Section 3 is discussed which used a standard ram accelerator projectile and a more realistic propellant mixture. This experiment was initially reported in Ref. 42; additional details can be found there.

A schematic of the experiment is shown in Fig. 8. The projectile is accelerated by a conventional ram accelerator stage to the desired test velocity and then passes into a stage of inert gas to “strip” the combustion wave. The projectile then passes into the test stage consisting of a mixture similar to the starter stage, only with slightly less nitrogen dilution. This experiment is in sharp contrast to the usual ram accelerator experiments, where the projectile enters the stage with the combustion wave already attached from the prior stage. The operation of ram accelerators is usually initiated by a complicated and unsteady interaction with the obturator used to launch the projectile from the initial gas gun prelauncher.[43] In the present experiment, the projectile enters without a combustion wave, thus allowing the formation and stabilization process to be observed.

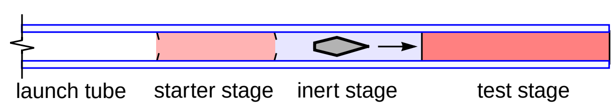

Fig. 8 Schematic of ram accelerator experiments with combustion wave stripped from the projectile.

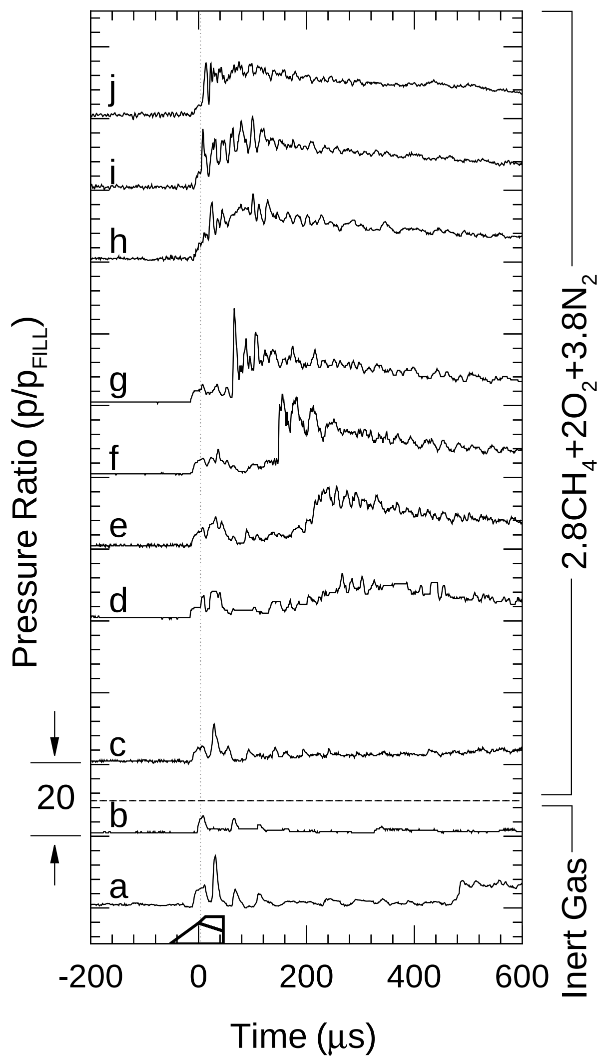

Fig. 9 Pressure data from ram accelerator experiment with combustion wave stripping. Note ignition in wake.

The pressure traces from this experiment are shown in Fig. 9. The traces are synchronized with the projectile. A small silhouette of the projectile, scaled to the velocity, is shown for comparison. The projectile transitioned from the inert stage into the combustible stage at Mach 4.2. The combustible mixture was $2.8CH_4+2O_2+3.8N_2$. The inert stage was an identical mixture, only with the oxygen exchanged for additional nitrogen ($2.8CH_4+5.8N_2$). Pressure traces a and b in Fig. 9 are from the inert stage. The shock activity observed in the vicinity of the projectile

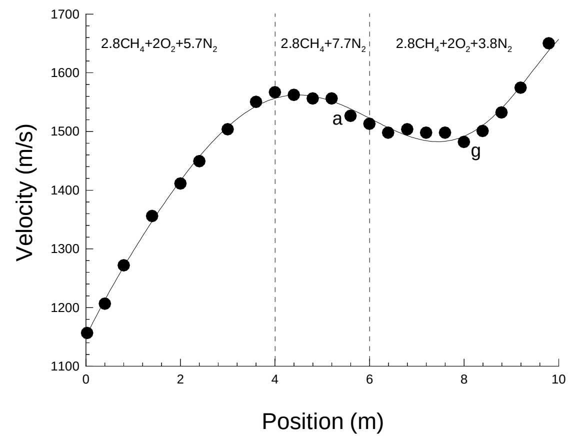

Fig. 10 Velocity–distance data for the combustion stripping experiment.

is the oblique shock from the nose cone reflecting between the tube wall and projectile body. [44] After the projectile transitions to the combustible mixture (trace c), no immediate change in the pressure wave form is observed. By trace d, however, a combustion wave is observed to form in the projectile wake and steepen into a strong shock. By trace h, the wave reaches the projectile and stabilizes there, *reestablishing ram accelerator drive.* The projectile velocity throughout this experiment, as determined by EM probes tracking a magnet carried on board the projectile, is shown in Fig. 10. The projectile is initially accelerated to 1550 m/s, then decelerates due to drag as it coasts through the inert, combustion stripping stage. The projectile continues to decelerate as it enters the combustible test stage, until the combustion wave is reinitiated and reaches the projectile. The local minimum velocity, occurring about 8 m into the ram accelerator, corresponds to the pressure trace g in Fig. 9, where the combustion wave is observed to reach the projectile. The fact that ram accelerator drive has been reestablished is proven by the steady acceleration of the projectile from the 8 m to the 10 m position, where the projectile exits the stage. The observed acceleration in this period agrees well with that predicted by the thermally choked model of ram accelerator performance.

Additional experiments with ram accelerator projectiles injected into combustible gases from inert gases are reported in Ref. 45. At Mach numbers below Mach 3.6, no combustion activity was observed and ram accelerator drive could not be reestablished. At Mach numbers greater than Mach 3.6, if the amount of nitrogen dilution was reduced to $2.8CH_4+2O_2+3N_2$ the combustion wave initiated in the wake swept over the projectile, resulting in an "unstart" and only imparted a transient acceleration on the projectile. These results suggest that the stable combustion wave observed in Fig. 9 can only be realized for a very special set of conditions. A complete discussion of the gas dynamic limits to operation of the ram accelerator as a function of the projectile Mach number and the mixture chemistry is found in Refs. 45 and 46.

The combustion wave observed to develop in the wake of the ram accelerator projectile in Fig. 9 is remarkably similar to the wake ignition phenomenon obtained with spheres in Section 3. This result is unique to the condition of tube confinement. The ability of the combustion wave to stabilize on the ram accelerator projectile is likely a result of the projectile shape and the mixture formulation.

5. Discussion

The wake initiation observed in Fig. 4b is very different than the unconfined results discussed in Section 2 above and in Refs. 22 and 35. In the large diameter detonation chamber, the detonation was observed to originate from the sphere itself, not the wake. Also, only nonreacting bow shocks from the sphere or free-running detonations were observed; the combustion wave in Fig. 4b was never seen in the unconfined experiments. The detonation initiation mechanism of Fig. 4b may be related to the well known phenomenon of deflagration to detonation transition (DDT). In DDT, the volumetric dilation of combustion products from an initially slow flame (deflagration) generates compression waves which propagate ahead of the flame front, coalescing into a shock. As the flame proceeds into the gas which has been precompressed by the shock, it accelerates due to both the shock heating of the gas and the fact that the flame becomes increasingly turbulent. A positive feedback is established between the accelerating flame and the shock it is driving, until the shock strength is sufficient to autoignite the gas. The final stages of transition to detonation are sudden and are usually associated with explosions which occur between the shock and reaction front, the so-called "explosion in the explosion."[32–34] Current thinking on this phenomenon suggests that a combustion wave will always accelerate to the fastest propagation speed consistent with the boundary conditions, which is usually CJ detonation.[34] This phenomena is almost exclusively observed in confined environments (tubes which are tens to hundreds of tube diameters long). In the present experiments, the projectile bow shock may play the role of the leading shock wave, while the combustion wave accelerates to overtake it.

The entrance diaphragm was shown to have a pronounced influence on the initiation of detonation in Section 2. For the results in a confining tube, the diaphragm impact can be ruled out as the detonation initiation source, since the sphere was always observed in supersonic flight at the first pressure transducer after the diaphragm. Had the sphere impact on the diaphragm directly initiated detonation, a detonation would have been immediately observed. The role of the diaphragm cannot be ruled out, however, as a possible ignition source for the combustion wave observed to originate from behind the sphere. The actual ignition mechanism remains unclear; boundary layer ignition and ignition by the multiple reflected oblique shocks are possibilities. However, once ignition occurs, the combustion wave is able to steepen into a strong shock and overtake the sphere, a phenomenon not observed in unconfined experiments.

Figure 6 shows the quantitative significance of the effect of confinement. The Lee-Vasiljev theory predicts a critical pressure (~1 bar for the mixture and sphere size used here) below which the sphere should not be able to initiate detonation. This critical pressure is a result of the fact that the critical energy to initiated detonation depends acutely on the detonation cell size ($E_c \sim \lambda^2$ for cylindrical detonations), which in turn is inversely proportional to the initial pressure. The results from the large diameter detonation chamber agree with this theory; the sphere could not initiate a detonation below 0.9 bar even if the sphere was launched at speeds in excess of the CJ speed. In a confined tube, however, the sphere is capable of initiating detonation at as low as 0.25 bar and at Mach numbers below Mach 3.5 via the wake ignition mechanism.

The relevance of this mechanism to the ram accelerator is demonstrated in Section 4. By stripping the combustion wave from the projectile via a stage of inert gas and then injecting it back into a combustible mixture, the ignition and stabilization of the combustion wave on the projectile can be observed. This mechanism is not possible in an unconfined flow, nor is this mechanism dependent on the projectile drag. Ignition here is more likely a result of multiple oblique shock reflections or boundary layer interactions on the tube wall. Hence, the ram accelerator, unlike the external propulsion accelerator, does not rely on drag as the mechanism of initiating and stabilizing combustion. Only certain ranges of propellant heat release and projectile Mach number allow the combustion wave to stabilize on the ram accelerator projectile. [45,46]

6. Conclusions

The flow field of the ram accelerator is dominated by the effect of confinement. While simple theories of detonation initiation by blunt projectiles due to Lee[23] and Vasiljev[24] are successful in predicting the outcome of experiments in unconfined environments, these theories have little, if any, relation to the combustion processes which occur in the ram accelerator. Confinement results in a long oblique shock train behind the projectile which is intimately coupled with a viscous and turbulent wake. This flow field allows combustion waves to form and propagate toward the projectile, a phenomenon which would not otherwise be observed in unconfined experiments. For experiments with a sphere in a sensitive, detonable mixture (hydrogen/oxygen with argon dilution), the combustion wave propagates past the projectile and continues as a free-running detonation. In experiments using a conventional ram accelerator projectile in a methane/oxygen/nitrogen mixture, however, the combustion wave is able to stabilize on the projectile and exert significant and steady thrust. These results suggest that the combustion mechanism in the subdetonative ram accelerator is not simply detonation. Nor is it shock-induced combustion, since shock induced combustion would result in combustion occurring at a fixed and finite distance downstream of the igniting shock wave for a given Mach number. Instead, the combustion process in the ram accelerator is more similar to the accelerating combustion waves observed in the DDT process. For a judicious selection of projectile and propellant mixture, such a wave can stabilize on the projectile, resulting in quasi-steady acceleration of the projectile in accord with the thermally choked model.

While the present results have not provided any great insight to the detailed mechanism of combustion in ram accelerators, the experiments discussed here suggest a way to study this issue further. Injecting the projectile into a combustible mixture from an inert mixture provides a much “cleaner” way of studying the combustion initiation and stabilization process than the usual starting “trick” involving a complex and unsteady interaction between the obturator, entrance diaphragm, and residual launch tube and ram accelerator gases.[43]

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