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Review of Propulsion Applications of Detonation Waves

K. Kailasanath*
U.S. Naval Research Laboratory, Washington, D.C. 20375

Applications of detonations to propulsion are reviewed. First, the advantages of the detonation cycle over the constant pressure combustion cycle, typical of conventional propulsion engines, are discussed. Then the early studies of standing normal detonations, intermittent (or pulsed) detonations, rotating detonations, and oblique shock-induced detonations are reviewed. This is followed by a brief discussion of detonation thrusters, laser-supported detonations and oblique detonation wave engines. Finally, a more detailed review of research during the past decade on ram accelerators and pulsed detonation engines is presented. The impact of the early work on these recent developments and some of the outstanding issues are also discussed.

Introduction

THE power of detonations has been well recognized. For example, it has been estimated that a 20-m^2 detonation wave operates at a power level equal to that received by the Earth from the sun.[1] The difficulty in harnessing this power efficiently has been a major stumbling block in the development of propulsion systems based on detonations. Although there are no practical propulsion systems (to the author's knowledge) using detonations, it has not been due to lack of effort. As will be discussed, there have been serious attempts, at least since the 1940s.

In principle, detonations are an extremely efficient means of burning a fuel–air mixture and releasing its chemical energy content. However, detonations have been explored for propulsion applications only for the past 50 years or so[2,3] because of the difficulties involved in rapidly mixing the fuel and air at high speeds and initiating and sustaining a detonation in a controlled manner in fuel–air mixtures. Recently, there has been a renewed interest in the application of detonations to propulsion, and hence, it is timely to review the past work. There have been several review papers (e.g., Refs. 4–8) in the past dealing with particular applications of detonations to propulsion. Here, an attempt is made to include the work reported in those papers, put them in the context of other related research, include additional studies, and extend the review to more recent papers.

In this paper, the status of propulsion applications of detonations is reviewed. First, a cycle analysis is performed to show that the efficiency of a detonation cycle is close to that of the constant-volume Humphrey cycle, which is much more efficient than the constant-pressure Brayton cycle, characteristic of most conventional propulsion systems. Other advantages of detonations are also discussed. Then a review of the early attempts to use detonations for propulsion is presented. After a brief discussion of the possible reasons for the successes and failures of the early attempts, more recent work during the 1980s on oblique detonation wave engines is reviewed. This is followed by a detailed analysis of the ram accelerator in the detonative mode and the pulsed detonation engine, a topic of great current interest. Finally, some observations from the lessons learnt in the past and their potential implications for further development of detonations for propulsion applications are presented.

Why Detonations?

As mentioned before, very rapid material and energy conversion is a key feature of detonations. This rapid burning or material conversion rate, typically tens of thousands of times faster than in a flame, can lead to several advantages for propulsion, such as more compact and efficient systems. Because of the rapidity of the process, there is not enough time for pressure equilibration, and the overall process is thermodynamically closer to a constant volume process than the constant pressure process typical of conventional propulsion systems. To illustrate this point, three idealized thermodynamic cycles are compared in Fig. 1.

For purposes of comparison, the only process that is different in the three cycles is the mode of energy conversion or heat addition. For the three cases, heat is added at constant pressure, constant volume, or in a detonation. Hence, the three cycles have been referred to as constant pressure, constant volume, and detonation cycle, respectively. The amount of heat added is kept the same for the three cycles. In all cases, the fuel–air mixture is initially compressed adiabatically from 1 to 3 atm before heat addition. After heat addition, the products of combustion are expanded adiabatically to 1 atm. Finally, the system is returned to its initial state. The work done during the three cycles is obtained from the area enclosed (Fig. 1). Because all processes except for heat addition have been maintained, the work done or relative thermodynamic efficiency of the three combustion processes can be obtained by comparing the three areas. For the efficiency, the work output is divided by the heat input, which was set to be the same for the three cycles. The thermodynamic efficiencies for the three cycles are 27% for constant pressure, 47% for constant volume, and 49% for detonation. From Fig. 1 and the given values, we see that the thermodynamic efficiency of the detonation cycle is close to that of the constant volume cycle. The process itself is different with a decrease in specific volume and a significantly higher pressure being attained during detonations.

One of the factors that could change the relative efficiencies is the amount of initial compression. To illustrate this, several such cycles were computed with all factors held the same, except for the amount of initial compression. There is some change in the relative values, but in all of these cases the efficiency of the detonation process is close to that of the constant volume process and significantly better than that of the constant pressure process. Other factors that could affect the relative efficiencies are the amount of energy conversion (heat addition) and the rates of initial compression (if any) and final expansion. These do not drastically alter the results just presented.

It is important to emphasize that the preceding comparisons are for idealized thermodynamic cycles for systems operating in a steady state and are not representative of any particular propulsion system. As will be discussed, attempts at developing engines using a steady or stabilized detonation wave have been less successful than those taking advantage of the unsteady aspects of detonation waves.

Several other advantages have been stated for using detonations in propulsion devices, and these will be brought up, as appropriate, when the different applications of detonations are discussed.

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*Head, Center for Reactive Flow and Dynamical Systems, Laboratory for Computational Physics and Fluid Dynamics, Code 6410. Associate Fellow AIAA.

Early Research

Although basic studies and applications of detonation have been undertaken for a very long time, specific references[2,3] to propulsion appear in the literature only in the 1940s. Even at this early time, both standing (or stabilized) and unsteady (intermittent) detonations were explored. In the work of Hoffmann,[2] both gaseous (acetylene) and liquid (benzene) hydrocarbon fuels were employed with oxygen. Intermittent detonation appears to have been achieved, but attempts to determine an optimum cycle frequency were less successful. The development of the concept of pulsed detonation engines (PDEs) has been traced back to this pioneering work in a number of papers. The proposals of Roy[3] inspired further work in France on the design of systems to stabilize combustion in supersonic flows (e.g., Ref. 9). Soon work was also begun in the United States. Bitondo and Bollay[10] conducted an analytical study that indicated that a pulsating detonation engine can be helpful for helicopter propulsion. Gross,[11] Gross and Chinitz,[12] Nicholls et al.,[13] and Nicholls and Dabora[14] studied means to stabilize detonation waves for applications to hypersonic ramjet propulsion. The possibility of using oblique detonations was also introduced.[15] More recent extension of these ideas will be discussed in the sections on "Oblique Detonation Wave Engines" (ODWEs) and "Ram Accelerators."

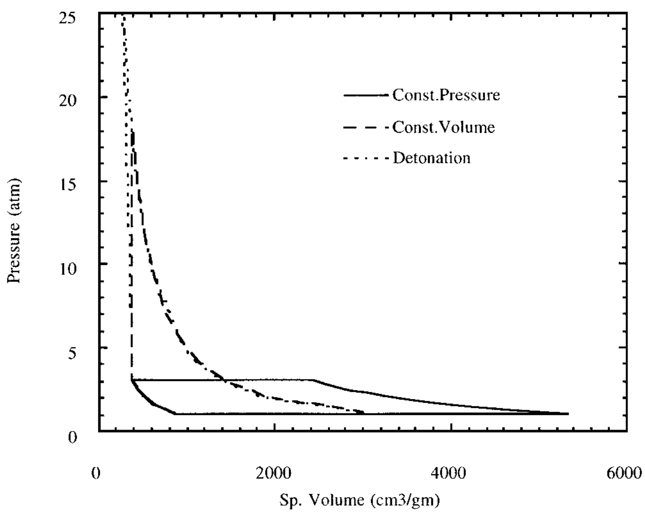


Fig. 1 Comparison of idealized thermodynamic cycles for constant pressure, constant volume, and detonation modes of combustion.

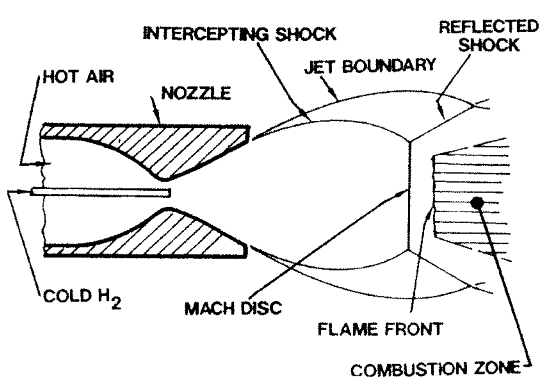


Fig. 2 Schematic of a standing detonation wave at the exit of a nozzle (from Ref. 14).

Stabilized Normal Detonations

First we briefly look at some of the early experiments to stabilize detonation waves. A schematic of an experiment is shown in Fig. 2 (from Ref. 14). Cold hydrogen gas injected at the throat of a convergent–divergent nozzle mixes with the high-pressure, high-temperature air flowing through the nozzle. Because of the short residence time and rapid drop in temperature, combustion does not occur within the nozzle. The nozzle is operated highly underexpanded, so that further expansion occurs outside resulting in a complex system of shock waves, a key feature of which is the Mach disk, a nearly normal shock. The conditions behind this Mach disk are such that ignition and energy release occur just behind it. If the energy release is closely coupled to the shock wave, a detonation will be established. Whether or not a detonation is established will depend on the induction time behind the Mach disk, which in turn will depend on the pressure, temperature, and mixture composition. Application of such steady-state detonations to propulsion were explored and performance comparable to conventional ramjets were reported for appreciably higher flight Mach numbers.[15]

Intermittent Detonations

Concurrent with their work on stabilized detonation waves, Nicholls et al.[16] also explored the concept of intermittent (or pulsed) detonation waves for propulsion applications. Both single-cycle and multicycle operations with hydrogen and acetylene as fuels and oxygen and air as oxidizers were demonstrated. The basic setup was a simple detonation tube, open at one end with coannular fuel and oxidizer injection at the closed end as shown in Fig. 3 (from Ref. 16). Thrust, fuel flow, airflow, and temperature measurements were made over a range of operating conditions. When the spark plug was located 2 in. (5.08 cm) or 5 in. (12.7 cm) from the end of the mixing plane, spasmodic firing was observed suggesting problems with fuel–air mixing. However, with the spark plug located 10 in. (25.4 cm) downstream, periodic detonations for a range of mixtures were reported. For a hydrogen–air mixture, a specific impulse of 2100 s was attained along with a cycle frequency of 35 Hz. They also presented a very simplified theoretical analysis that gave overall results very much in agreement with their experimental data on hydrogen but less with the case of acetylene.[16] However, they realized that the agreement was partly fortuitous because the measured thrust-time history was significantly different from the theoretical result (Fig. 4, from Ref. 16). Note that they also attempted initiation from the open end but were not successful.

A setup similar to that of Nicholls et al.[16] was constructed by Krzycki,[17] who used automotive spark plugs for ignition. He demonstrated operation at 60 Hz with propane–air mixtures, but there is some doubt whether the device was operating in the detonative mode

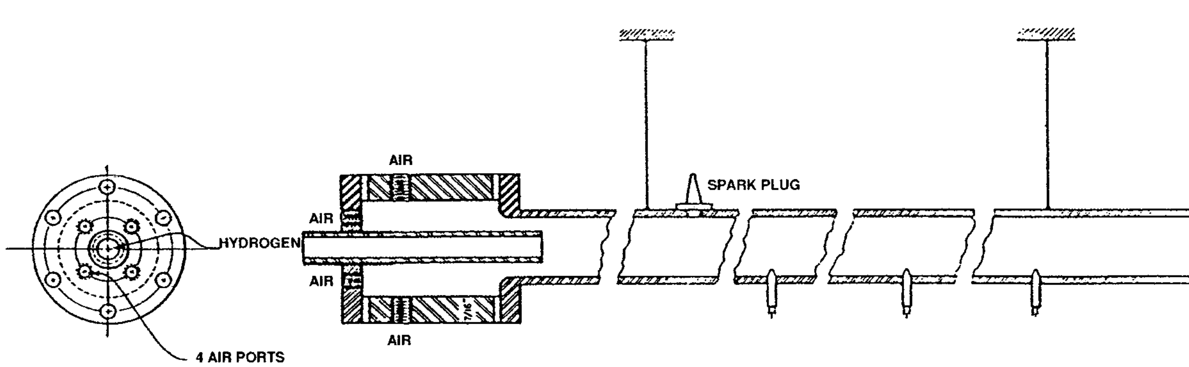


Fig. 3 Schematic of an experimental setup for multicycle detonation studies (from Ref. 16).

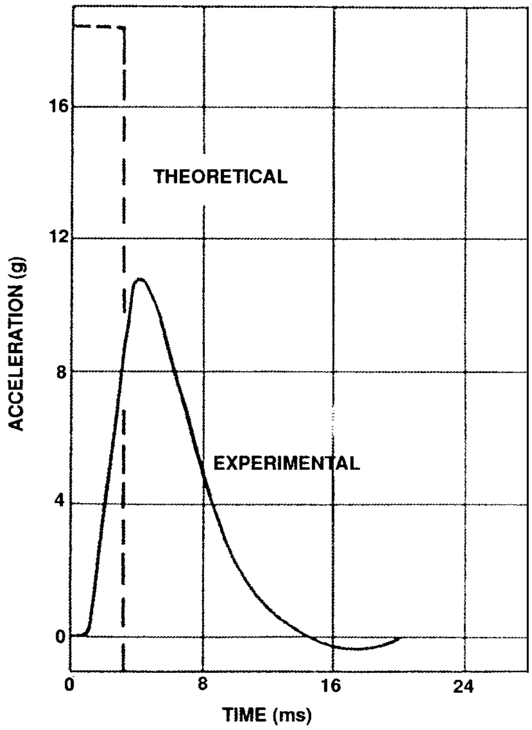


Fig. 4 Comparison of theoretical and experimental results on time histories of detonation tube acceleration for a 50% acetylene–oxygen detonation (from Ref. 16).

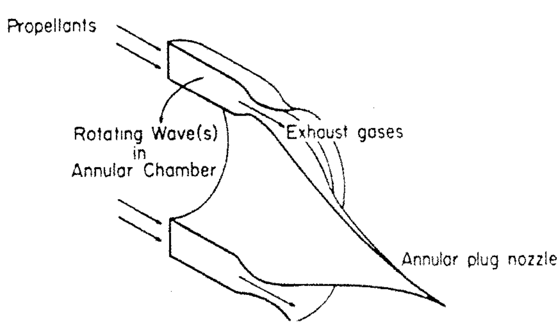


Fig. 5 Possible configuration for a rotating detonation wave engine (from Ref. 19).

or merely as a pulse jet engine due to the low initiation energies employed. His overall conclusion was that although thrust was possible from such a device, practical applications were not promising.

Rotating Detonation

Another interesting concept that was explored was that of a rotating detonation wave rocket motor.[18–20] Here gaseous fuel (hydrogen or methane) and oxygen were continuously injected into an annular combustion chamber and ignited using spark plugs. A unidirectional detonation wave was created after transition from a deflagration wave and the exhaust gases were expelled through an annular nozzle. Such a system is shown in Fig. 5 (from Ref. 19). The accompanying analysis indicated that the ideal performance is essentially the same as that of a conventional rocket engine, as long as the average chamber conditions and fuels used were the same. Furthermore, if there was significant mixing between the burned and unburned gases, the performance could actually be degraded.[19] Further work was done to extend the analysis to two-phase detonations[20] and to provide an explanation of some cases of shock-related combustion instabilities observed in liquid rocket motors.[21] However, multicycle experimental operation does not appear to have been achieved.

Oblique Shock-Induced Detonations

The work of Gross,[11] Gross and Chinitz,[12] Nicholls et al.,[13] Nicholls and Dabora,[14] and Dunlap et al.[15] led to an extensive ex-

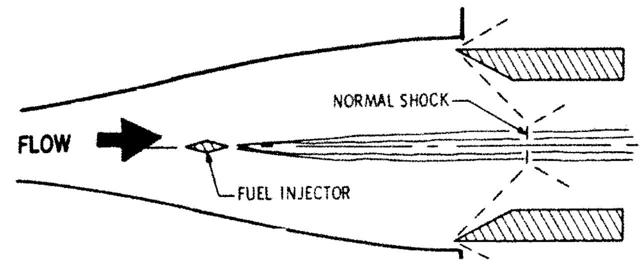


Fig. 6 Schematic of a normal shock-induced combustion (from Ref. 6).

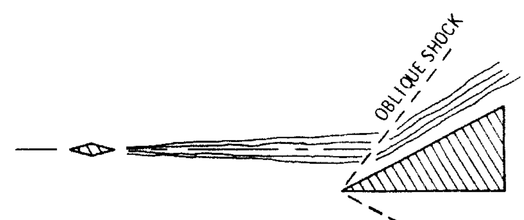


Fig. 7 Schematic of an oblique shock-induced combustion (from Ref. 6).

perimental study using a Mach 3 tunnel at the Arnold Engineering Development Center. A detailed review of this work during the period 1959–1968 is available,[6] and hence only a brief discussion is given here. The shock bottle experiments of Nicholls and Dabora[14] (Fig. 2) were reproduced, and a different configuration was developed. In this configuration [Fig. 6 (from Ref. 6)] combustion takes place behind a normal shock generated by oblique shocks induced by wedges. It has been argued that a detonation does not take place in this configuration because the normal shock wave is independently generated by the wedges and is not directly affected by the combustion.[6] The term "shock-induced combustion" was introduced to describe such phenomena. Whether a detonation occurs or not, their work led to the realization that a normal shock-induced detonation, a Chapman–Jouguet (C–J) detonation, was not essential for propulsion.[6] They investigated other configurations [Fig. 7 (from Ref. 6)] and concluded that oblique-shock-induced combustion is experimentally feasible. This was a significant conclusion because it has led to the future development of the ODWE and, to some extent, to the ram accelerator. Both of these propulsion applications will be discussed later in some detail.

Detonation Thrusters

In the 1970s a substantial effort[22–25] was undertaken at the Jet Propulsion Laboratory (JPL) to investigate the feasibility of using detonative propulsion for thrusters in the dense or high-pressure atmospheres of solar system planets. The primary reason for studying this concept was the potential for high performance for situations where the external pressures are high. Under such conditions, conventional thrusters become inefficient due to the lowering of the combustor to ambient pressure ratio. The JPL concept involved filling nozzles with hydrogen, helium, nitrogen, or carbon dioxide to simulate planetary atmospheres and then intermittently detonating a small quantity of condensed-phase explosives at the apex of the nozzle. Thrust is produced primarily from the momentum of the filler gases set into motion by the blast wave and by the expansion of the detonation products. Both theoretical analysis and experiments showed that a small quantity of explosives detonated within the nozzle filled with gases was sufficient to produce high specific impulse. Different types of nozzles and gases of different molecular weights were utilized. With a short-plug nozzle, there was a slight reduction in specific impulse with increasing ambient pressure but the results were virtually independent of the molecular weight of the ambient gases. However, with a long-cone nozzle, there was a progressive increase in the specific impulse with increasing ambient pressure for high molecular weight gases (carbon dioxide and nitrogen) and a decrease with increasing pressure for lower molecular weight gases (helium). A primary conclusion from the work at JPL was that detonation propulsion technology can be considered for producing both large velocity changes as a main propulsion system or for generating small velocity changes such as in attitude control propulsion. Although this can be considered to be one of the more successful applications of detonation to propulsion, one must remember that in this application, the details of the detonation process itself appear to be secondary and the working fluid is a nondetonable gas mixture.

Laser-Supported Detonations (LSDs)

Another intriguing concept proposed in the 1970s was the use of lasers to propel objects to low Earth orbit.[26] The basic idea behind this propulsion concept is to use lasers to generate detonations and a high kinetic energy propulsive jet moving away from the object being propelled. The idea was not pursued very far due to the limited laser powers available then and the obvious atmospheric transmission problems. However, with the planned development of larger lasers under the Strategic Defense Initiative program, the concept was explored in some detail (for example, see Refs. 27–29) in the late 1980s. In principle, a high controllable exhaust velocity can be achieved by a two-step process: In the first step the desired amount of propellant is formed as a gas layer near the surface and in the second step, the laser energy is directly deposited in this layer. The first layer can be generated either by transpiration of a liquid through a porous surface or by a laser prepulse in a two-pulse system.[27] In a two-pulse system, a very low-intensity, long-duration (on the order of seconds), laser prepulse is used to ablate enough gas from the surface of the solid/liquid propellant to form a buffer gas layer. A second, high-intensity, short-duration laser pulse irradiates the gas layer, depositing its energy in the gas layer just before reaching the propellant surface. A shock wave then propagates out through the gas layer, back toward the laser, heating and accelerating the gas layer. What is effectively a laser-supported detonation (LSD) is formed by the shock wave followed by the recombination zone behind it.[28] In theory, a high specific impulse (~ 1000 s) can be generated with simple propellants such as ice. However, the real problems of building a large enough laser and safely transmitting enough energy to the desired location remain, and to the best of the author's knowledge, LSDs have not been conclusively demonstrated.

Another concept using lasers to initiate detonations was proposed by Carrier et al.,[30] Fendell et al.,[31] and Carrier et al.[32] They conducted theoretical and experimental feasibility studies of a supersonic combustor based on a stabilized, conically configured oblique detonation wave (ODW). The stabilized detonation wave is formed by the interaction of a train of spherical detonation waves, each directly initiated by a brief, localized deposition of energy from a very rapidly repeated pulsed laser. The laser is focused on a fixed site in the combustor where there is a steady, uniform supersonic stream of detonable gases. Initiation of an individual spherical detonation wave by a single laser pulse was achieved,[32] but further results have not been reported.

ODWEs

With the renewed emphasis on hypersonic flight vehicles in the 1980s, extensive investigations were conducted of supersonic combustion concepts. However, these studies will not be discussed here unless they specifically invoke detonations. Various versions of these concepts have been called by special names such as detonation-driven ramjets (dramjets),[5] but these essentially involve stabilized ODWs and can be traced to the original concept proposed in the 1950s by Dunlap et al.[15] Basically, if a premixed fuel–air mixture flows at a velocity greater than the C–J velocity, then a normal detonation wave cannot be stabilized. The hope was that under these conditions, an ODW can be stabilized on a wedge-shaped object such that only the normal component of the flow becomes sonic or subsonic. That is, most of the flow in the combustor will remain supersonic. A schematic of the dramjet is shown in Fig. 8 (from Ref. 5). Here, fuel is injected into the incoming airstream, mixes rapidly with it and is ignited behind the centerbody of a ramjet, which acts as a stabilizer, holding the oblique wave. It is similar to a conventional ramjet except for the close coupling between the reaction waves and the leading shock waves resulting in a detonation wave. The performance of such a device has been calculated and shown[5] to be less than that of an ideal ramjet over a range of Mach numbers from 5 to 30. Issues such as the presence of inlet shocks and the ability to mix rapidly enough to obtain a detonable mixture were not addressed in this paper.[5]

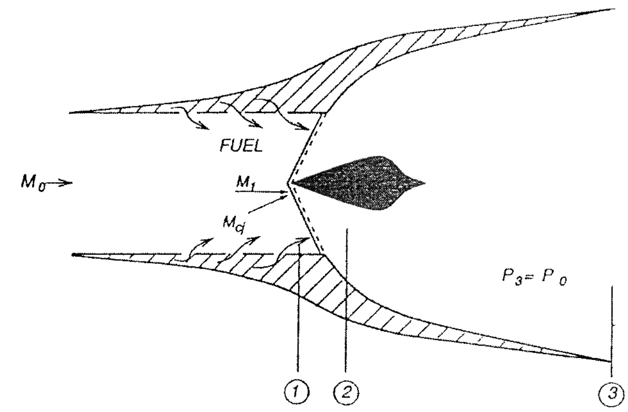


Fig. 8 Schematic of a dramjet (from Ref. 5).

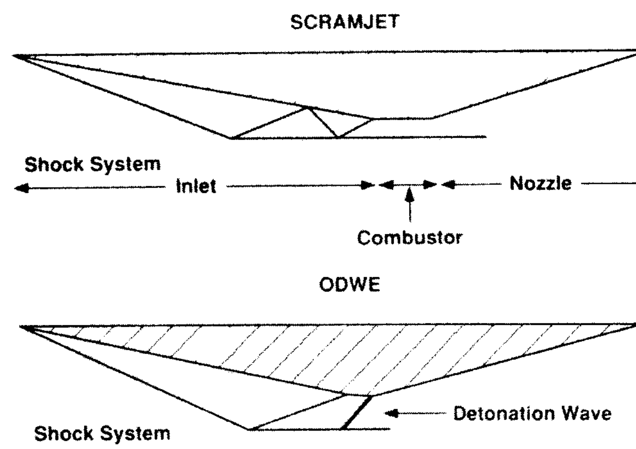


Fig. 9 Schematic of shock structure for scramjet engine and an ODWE (from Ref. 33).

A representation closer to scramjet engines is shown in Fig. 9 (from Ref. 33). Here the inlet shock system is shown but the link between the inlet shocks and the ODW is left unclear. Once again, it is assumed that fuel–air mixing occurs rapidly enough and that the oblique shock wave is strong enough so that chemical reactions occur close behind it and are coupled to it. Analysis of a conceptual vehicle using such an ODWE showed that it has better performance than an equivalent scramjet for Mach numbers over 15. The main advantage arises from the reduced length of detonation engines. In a related work, the issue of mixing inhomogeneities and their effect on the detonation wave were addressed numerically.[34] There have also been several other studies examining the feasibility and performance of detonation wave ramjets.[35,36] All of these concepts essentially rely on rapid ignition and combustion occurring behind an oblique shock wave and the coupling between the two processes resulting in a stable structure. A difference between these more recent works and the earlier ones is the realization that in many situations shock-induced combustion does not lead to detonations. However, none of these studies seem to have led to the actual building and testing of an ODWE.

Ram Accelerators

If the solid body anchoring the oblique shock or detonation is free to move, the integral of pressure forces around the body can result in a net force causing the body to accelerate or decelerate. This is essentially the concept behind the ram accelerator, a propulsion concept proposed[37,38] in the late 1980s. In a ram accelerator,

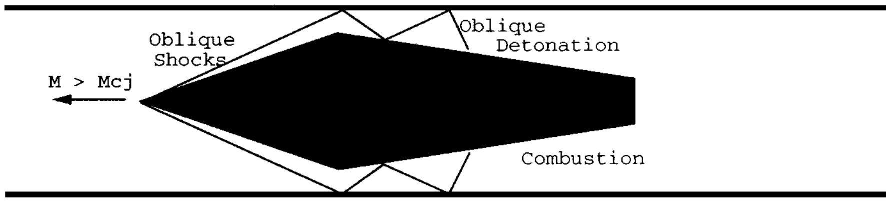


Fig. 10 Schematic of a ram accelerator in the detonative mode.

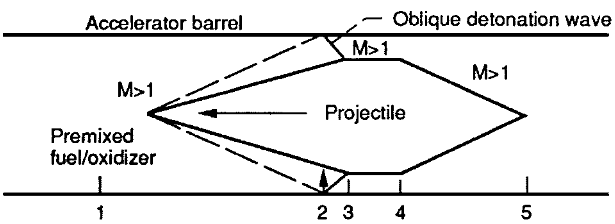


Fig. 11 Early concept of the detonative mode (from Ref. 37).

a projectile that resembles the centerbody of a ramjet travels at a supersonic speed through a premixed fuel–oxidizer–diluent mixture enclosed in a tube. Because the projectile travels at supersonic speeds, oblique shock waves are formed at the nose of the projectile, and they subsequently reflect from the side walls of the tube and the projectile body. Depending on the strength of these oblique shocks, ignition may occur after the initial shock or subsequent reflections. Depending on the velocity of the projectile, different modes of combustion and correspondingly different modes of operation of the system are possible. When the velocity of the projectile is greater than the C–J velocity, an ODW may be stabilized on the projectile resulting in the detonative mode of operation. A schematic of the ram accelerator operating in the detonative mode is shown in Fig. 10. From the early days, detonation has been discussed as a means to attain very high velocities, including escape velocities.[37] In Ref. 37 and several subsequent investigations, the structure of the detonative mode was described by the schematic diagram shown in Fig. 11. The projectile nose cone angle and the sound speed in the mixture selected were tailored to avoid combustion behind the initial shock wave, but to provide initiation behind the first shock wave reflected from the tube wall. Emphasis was also placed on having the first reflected shock wave strike the projectile body just aft of the shoulder.[37] If the system needed to be designed so precisely, successful operation would indeed be difficult in practical situations. Further research has shown that the system is far more stable, and the particular scenario shown in Fig. 11 actually occurs just prior to system failure. There were early reports of successful attainment of superdetonative projectile velocities,[39] but the experimental emphasis shifted to the successful development of subdetonative modes of operation except at the Institute of Saint-Louis (ISL), where research on the detonative mode has continued.[40–42]

Numerical simulations[43,44] and theoretical studies[45,46] based on simplified analytical models of superdetonative ram accelerators were started in the early days and have made a significant impact over the past decade. These early studies confirmed the potential of ram accelerators to accelerate efficiently large masses to escape velocities and low Earth orbit. The steady-state simulations of Yungster[47] highlighted the role of the projectile velocity (or Mach number) and showed that detonation could occur at different locations along the projectile body depending on the projectile Mach number (defined as the ratio of the velocity of the projectile to the speed of sound in the premixed mixture). This work also raised the issue of combustion in the boundary layers along the projectile.

The projectile velocity changes continuously in the ram accelerator, and therefore, steady-state simulations can at best be thought of as trying to characterize an instantaneous snapshot of the system. The importance of the transient processes was first highlighted in the work of Li et al.[48] This, as well as subsequent work,[49] has shown the importance of taking into account the time-dependent

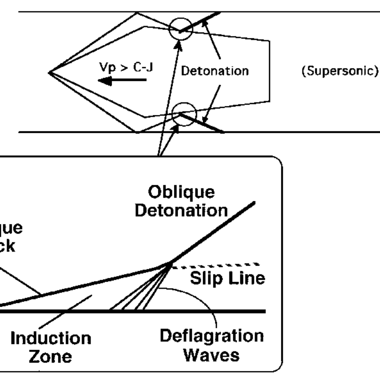


Fig. 12 Schematic showing the detailed structure of an oblique detonation and its relation to the detonation structures in ram accelerators.

nature of the flow in the ram accelerator in describing phenomena such as unstarts and other system failures. Computational studies of the starting aspects of ram accelerators and the role of viscous effects have also been conducted.[50–52] Experimental efforts have primarily focused on the nondetonative mode, except at ISL.[40–42] Before discussing some of the experimental results and the difficulties encountered in the practical development of ram accelerators in the detonative mode, two critical issues need to be discussed. One issue is the actual structure of ODWs and the other is the stability of such detonation waves during transient operation.

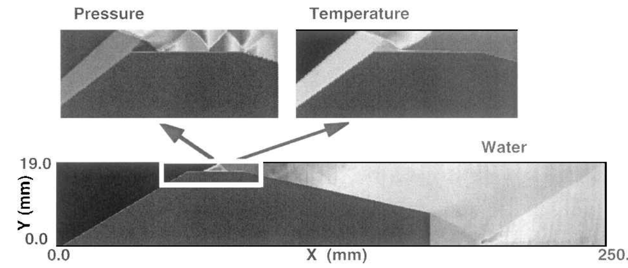
Structure and Stability of ODWs

A key issue in the development of the ODWE and the ram accelerator is the structure and stability of ODWs. Although the use of ODW was suggested as early as 1958,[15] the stability of such waves was implicitly assumed and questions about their detailed structure were not considered. Renewed interest in the late 1980s led to a theoretical analysis of the supersonic flow of a combustible gas mixture past a wedge.[53] Reference 53 indicated that for approach velocities roughly 25% or more larger than the C–J velocity of the reactant mixture, ODWs can be stabilized over a useful range of wedge angles. For wedge angles greater than a critical value, the wave will detach from the wedge and form an overdriven detonation wave or a more complex shock-induced combustion wave. About this time, there were also numerical studies that showed that standing detonation waves can be established on a wedge under certain flow conditions.[53,54]

The early experimental efforts[6,13,14] were either focused on stabilizing a normal detonation wave in a duct or involved shock-induced combustion behind weak oblique shock waves. Therefore, it was not clear if ODWs could really be stabilized until some experiments in the late 1980s on the diffraction and transmission of detonations showed that they could be.[55,56]

More recently, the interest in ram accelerators has spawned a large number of studies of the structure and stability of ODWs.[57–61] The work of Li et al.[57–59] showed that the basic structure of an oblique detonation generated by a wedge is more complex than previously thought and consists of a nonreactive shock wave, an induction region, deflagration waves, and a detonation wave in which the pressure increase due to the energy release is closely coupled to the shock front. This basic structure and a schematic of how it might relate to the detonation waves in ram accelerator is shown in Fig. 12. These studies also showed that over a wide range of flow and mixture conditions, the basic detonation structure is stable and very resilient to disturbances in the flow. In agreement with theory,[53] the simulations also showed the existence of a critical angle beyond which an attached stable detonation does not occur.[59] Other recent studies have shown the same complex structure even with the inclusion of more complex chemical kinetic schemes.[60,61] The essential features of the complex ODW structure have also been confirmed by experiments.[4,62] Thus, a major conclusion from the recent research is that the structure of an ODW can no longer be assumed to be a straight oblique shock wave followed closely by energy release, and the complex structure can indeed be stabilized on wedge-shaped objects. Implications of this work on propulsion applications must be considered.

Although the schematic of Fig. 12 shows how to relate the basic ODW structure to that in ram accelerators, the actual detonation wave structure in ram accelerators is likely to be more complex because of the expansion waves and multiple shock waves that are generated due to the geometric complexity of the system.[63] The results from a study of the detailed structure of detonations in ram accelerators under a variety of flow conditions[63] are summarized in Fig. 13, where the detonation wave structure is shown for three flow Mach numbers. Recent experimental investigations have also revealed extremely complex detonation wave structures involving multiple shock waves under certain conditions.[64] In spite of their complexity, all of these structures appear to be inherently related to the basic three-wave structure of oblique detonations shown in Fig. 12. However, this appears to be an area of research that will continue for a while.



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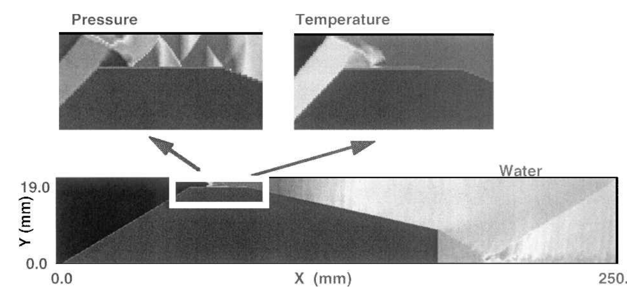
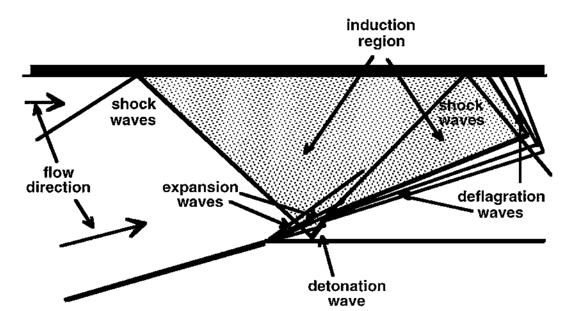
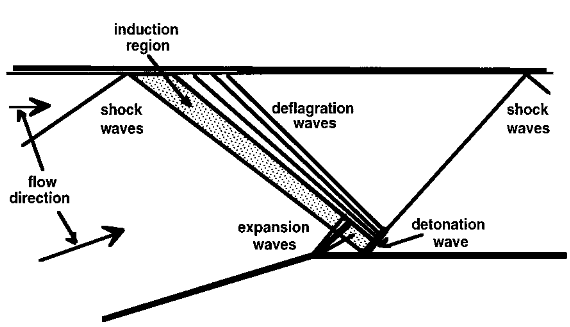


b) Case B Mach = 9.15

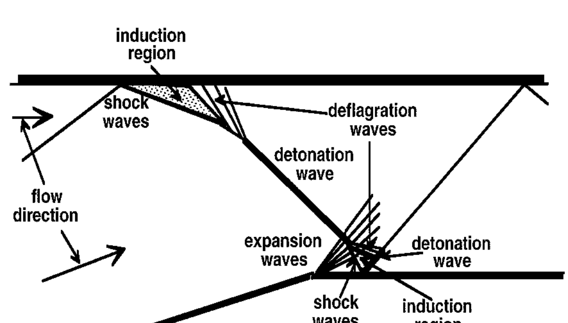
Fig. 14 Visualization of the flowfield during the acceleration of the projectile shown in Fig. 5 from Mach 8 to 10 at two instants.



a)



b)



c)

Fig. 13 Detailed structure of detonations in ram accelerators operating at a) Mach 7.6, b) Mach 8.0, and c) Mach 8.4 (from Ref. 63).

Transient Nature of Detonation Waves in Ram Accelerators

The second important feature revealed by the recent studies is the inherent transient nature of detonation waves in configurations such as the ram accelerator. When the concept of ram accelerators in the detonative mode was first proposed, it was thought that the leading shock wave (from the nose of the projectile) should reflect from the tube walls such that it impinges exactly at the shoulder of the projectile. This will maximize the thrust and, hence, acceleration. However, if the system were designed so precisely for one condition, its off-design performance could be unacceptable. Furthermore, simulations have shown that as the projectile accelerates, the detonation wave structure tends to also move.[49] To illustrate the dynamics of detonations in the ram accelerator, two photographs of the flowfield from a simulation (where the projectile accelerated from Mach 8 to 10) are shown in Fig. 14. In case A the projectile Mach number is 9.05 and in case B it is 9.15. For both cases, the main illustrations show the concentration of water vapor with the two inserts showing the pressure and temperature in a selected region of the flowfield. At the instant shown in Fig. 14a (case A), the pressure and temperature behind the first reflected shock wave are not very high, and combustion and energy release (as indicated by the water vapor concentration) takes place only behind the second reflected shock wave. That is, the detonation can be said to occur behind the second reflected shock wave. By the time the projectile has accelerated to Mach 9.15, the leading shock wave has strengthened, raising the pressure and temperature behind the first reflected shock wave and causing the detonation to occur there.

The behavior just discussed is seen throughout the operation of the ram accelerator in the detonative mode. That is, detonation waves in ram accelerators are dynamic and move from shock wave to shock wave as the projectile accelerates. Eventually, the detonation would occur just after the first shock wave, and the whole system will cease to operate because there will not be any positive thrust. Furthermore, the detonation wave will run in front of the projectile, creating a situation similar to the classical unstart phenomena in ramjets. Such unstarts and detonations occurring after a different number of reflections have also been noted in experiments.[42] Hence, the shape of the projectile has to be chosen carefully so that the detonation can move over the projectile body and still produce positive thrust over the regime of interest. A practical problem that has hindered the development of ram accelerators operating in the detonative mode is the change in the shape of the projectile due to material erosion, burning, and failure. This is currently being overcome by the use of steel cowlings.[42]

PDEs

The other major current propulsion application involving detonation waves is the PDE. The basic concept behind a PDE is simple. Detonation is initiated repeatedly at either the closed or the open end of a detonation chamber that is filled with a premixed fuel–air mixture. Figure 15 (based on Ref. 65) illustrates the concept for the case when the detonation wave is initiated at the closed end. As shown in this schematic, a one-dimensional planar detonation is initiated near the closed end of the detonation chamber and travels at the C–J velocity toward the open end. A set of rarefaction waves trail the detonation wave to reduce the velocity to zero at the closed end of the tube. When the planar detonation wave exits the chamber, another set of expansion waves is generated that travels toward the closed end. These waves evacuate the burned detonation products resulting in a cool, empty chamber that is ready to be filled with a fresh fuel–air mixture. The entire cycle repeats, resulting in a periodic high-pressure zone near the closed end of the chamber. The integrated effect of this high pressure over the closed end (representing a thrust wall) produces thrust. This is of course a very idealized picture of the system. Before discussing progress made in the recent years in developing a PDE, a brief review of the background is provided.

The early work on the use of intermittent detonations has already been discussed. In the late 1980s, this concept of using intermittent or pulsed detonations was reexamined experimentally at the Naval Postgraduate School.[66] An ethylene–oxygen detonation wave in a small-diameter tube was used as a predetonator to initiate detonations in a larger tube containing an ethylene–air mixture. Periodic fuel injection within the naturally aspirated tube resulted in an intermittent frequency of 25 Hz. Specific impulse estimated using the pressure time history and the amount of fuel consumed ranged from 1000 to 1400 s. The velocities of the observed waves (less than 1 km/s) are significantly below the C–J detonation wave velocities for the reported mixtures, indicating that a fully developed detonation wave was not formed.

The first purely computational study of the PDE reported in the open literature appears to be the work of Cambier and Adelman.[67] The system simulated consisted of a 50-cm-long main tube attached to a 43-cm-long diverging nozzle. Quasi-one-dimensional simulations using the Euler equations for unsteady flow were carried out with a total variation diminishing scheme and multistep finite rate kinetics. A detonation was initiated at the closed end of a tube filled with a premixed, stoichiometric hydrogen–air mixture at 3 atm. Overall performance calculated by integrating the instantaneous thrust and the fuel flow rates gave a specific impulse I_{sp} of about 6500 s and a range of operating frequencies up to 667 Hz. Issues of ignition energies and transition to detonation were not considered, and the difficulties with attaining rapid mixing of fuel and air was avoided by using a premixed fuel–air mixture. These assumptions are still typical of those used in more recent simulations.

The first look at the interactions between the flow inside the chamber and that outside appears to be the work of Eidelman et al.,[7] who simulated a cylindrical detonation chamber (about 15-cm diam

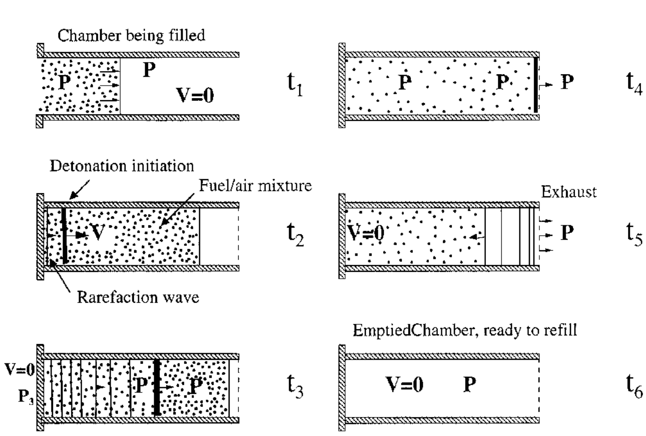


Fig. 15 Schematic of an idealized PDE showing various stages during one cycle of operation (adapted from Ref. 65).

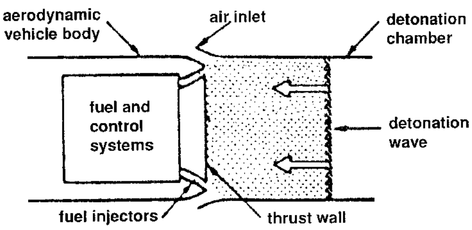


Fig. 16 Generic PDE device used for some computational studies where detonation is initiated near the open end (from Ref. 69).

and 15 cm long) with a small converging nozzle. In their two-dimensional simulations, a self-similar solution for a planar detonation was imposed near the open end and made to travel toward the closed end. The reflection of the wave from the closed end created a higher pressure at the wall than during initiation near the closed end. Hence, this mode of initiation was considered to be better. After the detonation left the chamber, the pressure in the chamber was observed to fall below the ambient resulting in ingestion of outside air. In subsequent works,[8,68,69] the same numerical techniques and models were used to investigate a slightly different configuration, where the nozzle at the aft end was removed and an inlet was introduced near the closed end. This configuration has become one of the popular systems for two-dimensional (and axisymmetric) numerical simulations. Again, detonation was assumed to be initiated at the open end and traveled toward the closed end. In this configuration, when the pressure falls below atmospheric in the detonation chamber, air is ingested through the inlets in the front even during static operations. Thus, a valveless, self-aspirating operation is possible. These simulations also introduced the discussion of open-end initiation vs closed-end initiation and their relative advantages. The current status of this issue will be discussed later.

Many of the early efforts on intermittent or PDEs have been reviewed in Ref. 7 and 8, where a link is also made between these detonation engines and pulse jet engines (which do not use detonative combustion). In addition, Ref. 8 provides a detailed summary of the numerical investigations conducted by the authors' group on a generic PDE device, shown in Fig. 16. A characteristic feature of this device is that the detonation wave is initiated at the open end and travels toward a thrust wall at the closed end. An advantage of this approach is that it is valveless and self-aspirating. Air is entrained into the chamber through inlets near the closed end when the pressure falls below atmospheric pressure during part of the cycle. Unsteady Euler simulations were used to study the operation of the device from static ($M = 0$) to supersonic ($M = 2$) conditions. As stated in Ref. 8, a proof of principle experimental demonstration of the PDE mode of operation where detonation is initiated at the open end still needed to be done. Furthermore, issues such as detonation initiation and structure and fuel–air injection and mixing also needed to be studied.

Bussing and Pappas[65] provided a detailed description of the basic operation of an idealfized PDE. They also reported some one-dimensional studies of PDEs burning hydrogen–oxygen and hydrogen–air mixtures. The detonation wave was initiated at the closed end in this engine using a high-temperature and high-pressure region. An advantage of this design is the confinement provided at the closed end, which should enable a more rapid initiation and establishment of a detonation. Both airbreathing and rocket mode of operation of this valved design was discussed. Lynch et al.[70] presented a computational study of an axisymmetric PDE with a straight inlet, very similar to that of Eidelman and Grossmann[8] and Eidelman et al.[69] Various inlet lengths from 1 to 12 cm and flight Mach numbers of 0.8 and 2.0 were studied. The results were similar to those reported earlier, except that some additional details of the detonation wave front and the air induction system were resolved in these studies. In a related work, Lynch and Edelman[71] showed that reductions in scavenging time (and, hence, overall cycle time) can be achieved by suitably shaping the inlet.

Bussing et al.[72] compared open-end initiation and closed-end initiation in a simple tube PDE geometry. Equivalent thrust production and fuel efficiency were observed for the two types of initiation.

Although a higher head-end pressure was attained during open-end initiation, the pressure continuously dropped for that case unlike the closed-end initiation, where a constant pressure region occurred for a while before reduction of the pressure to the ambient value. More recently, an experimental study has confirmed the differences in the observed pressure profiles and it has also been concluded that the maximum level of impulse attained is independent of the location of the detonation initiator.[73]

In the past few years, there has been a substantial growth in the appearance of papers related to the PDE and complete sessions have been devoted to the topic at annual AIAA/ASME/SAE/ASEE joint propulsion conferences. Because of space considerations, only selected papers from these years are briefly discussed here. Sterling et al.[74] conducted one-dimensional numerical investigations of a self-aspirating PDE operating for multiple cycles. A key observation from their studies was that only a portion of the detonation tube can be filled with fresh charge under self-aspirating operation. In spite of this limitation, they reported a specific impulse of 5151 s for a hydrogen–air system. However, they concluded that the ideal performance of such an engine is "near those of other hydrogen-fueled/air breathing engines."[74]

Several basic shock tube experiments related to the development of a hydrogen-fueled PDE were described by Hinkey et al.[75] These include the measurement of detonation wave velocities and deflagration to detonation transition (DDT) lengths for a range of equivalence ratios. As expected, the DDT lengths were found to be too large for practical applications, even in hydrogen–oxygen mixtures. Therefore, traditional techniques such as the use of a Schelkin spiral (see Ref. 76) were tried to reduce the transition length. A factor of 2–4 reduction was observed over the range of equivalence ratios investigated. This work[75] highlights the difficulties involved in obtaining a fully developed detonation in a short distance (as assumed in the conceptual studies and numerical simulations discussed earlier) and questions if the detonations reported in previous experimental investigations[16,17,66] were really fully transitioned from deflagrations. The specific impulses measured in their experiments (about 240 s for hydrogen–oxygen and 1200 s for hydrogen–air) were also stated to be in agreement with their analysis.

An interesting PDE concept presented by Bussing[77] was that of a rotary-valved multiple-pulsed detonation engine. Here, several detonation chambers are coupled to an air inlet and fuel source using a rotary valve as suggested in one of the early papers of Nicholls et al.[16] The rotary valves allow the filling of some detonation chambers while others are detonating or exhausting. Other papers include presentation of an overall PDE performance model[78] and the experimental characterization of the detonation properties of some fuels for use in PDEs.[79]

The importance of adequately mixing the fuel and oxidizer was highlighted by the experimental investigations of Stanley et al.,[80] who obtained very low sub-C–J velocities when injecting the fuel and oxidizer at different times and not taking extra effort to ensure that they were well mixed. The use of turbulence producing devices appeared to improve significantly the mixing and the attainment of higher velocities but also resulted in significant thrust losses. This study also showed that raising the initial pressure was beneficial. The computational studies of Eidelman et al.[81] showed that the PDE engine could operate even for a range of transitional detonation regimes that produced nonplanar or not fully developed detonations. Aarnio et al.[82] discussed two failure modes: DDT transition failure and premature ignition. In both cases, the system continued to operate, though there would be loss of thrust. In Ref. 82, detailed discussions of the pressure and thrust histories during a 5-Hz, 20-cycle operation are also provided (Fig. 17). The cycle to cycle variations of peak pressure have been attributed to the low sampling frequency used.[82] Both a direct measurement as well as the integration of the pressure histories were used to estimate the average I_{sp} from hydrogen–air systems to be between 1116 and 1333 s. The effect of the predetonator volume on the reduction of specific impulse was also shown to be a critical issue. The effects of inlets and nozzles were not considered in this study.

A conceptual design of a multitube PDE with a single air inlet duct was discussed by Pegg et al.[83] Time-dependent computational

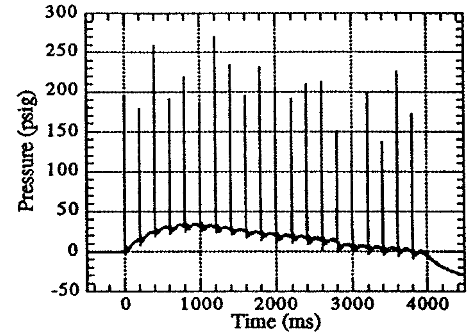


Fig. 17 Pressure history at one location from a PDE operating at 5 Hz for 20 cycles (from Ref. 82).

fluid dynamics analysis indicated that the inlet isolater/diffuser concept would work and did not allow enough time for the formation of destabilizing hammer shocks. Performance analysis including component efficiencies reported in the paper indicate that operational frequencies of the order of 75–100 Hz are required for the Mach 1.2–3 flights considered. Experimental data indicating multicycle operation at 100 Hz with a rich ethylene–oxygen mixture were presented by Sterling et al.[84] DDT enhancement devices and predetonators were used in the experiments. In spite of this, detonation waves did not occur all of the time, and when detonation waves failed, the tube became very hot and testing was suspended. Therefore, the maximum testing time was reported to be 0.5 s. In spite of this limitation, the two studies,[83,84] taken together highlight the possibility of PDEs burning hydrocarbon fuels for realistic missions.

Five different nozzle shapes and their effect on performance were studied computationally by Cambier and Tegner.[85] Their results indicate that the presence of a nozzle can affect the performance of the PDE by increasing the thrust delivery during the ignition phase. The bell-shaped nozzles appeared to give higher performance than shapes with positive curvature. Their results also showed that nozzles also affected the flow dynamics and, hence, the timing of the various phases of the engine cycle. In an experimental study of a conical exhaust nozzle, the authors of Ref. 86 noted improved performance (based on higher velocities, which were still sub-C–J) but did not see any effect on the blowdown process. More recently,[87] the effect of various nozzle shapes, including converging, diverging, and straight have been reexamined computationally. The converging sections of nozzles introduced shock wave reflections whereas diverging sections generated a negative thrust for a portion of the cycle due to overexpansion. In spite of these limitations, the overall conclusion of these studies was that "nozzles can drastically increase efficiency of the PDEs."[87] There is also some experimental evidence suggesting that propulsive performances can be increased by the addition of a nozzle.[73] However, factors such as the effect of the nozzles on detonation transmission and the detailed dynamics of the flow have not yet been elucidated. This appears to be an area that needs further investigation.

Other recent efforts have focused on demonstrating the operation of single- and multitube combustors coupled to an inlet using a rotary-valve mechanism.[88] The valve serves to both meter the airflow into the combustor and to isolate the inlet from the high pressures produced during the detonation cycle. Utilizing multiple combustors that fill and detonate out of phase allows the continual use of the inflowing air. Firing rates of up to 12 Hz per combustor were demonstrated for a hydrogen-fueled system. Several other issues related to the practical development of PDEs have been discussed by Bussing et al.[89] According to them, three of the more important engineering issues are the development of a valve-injection subsystem, an ignition system, and a low-volume predetonator.

The use of PDEs for rockets has been revived recently.[90] The rocket mode of operation is very similar to the description provided earlier of the airbreathing engine with ignition at the closed end, except that the oxidizer also needs to be injected into the system periodically. An advantage of PDEs for rockets would be their higher power density, thus enabling the development of more compact rockets. Reference 90 shows the pressure traces from a pulsed detonation rocket engine operating at 145 Hz on a hydrogen–oxygen mixture.

More recently, a two-tube rotary-valved PDE with flight-size components was operated at 40 Hz per combustor for 30 s with an ethylene–air mixture.[91] In addition, throttling of the device allowed operation at three thrust levels during a 10-s demonstration experiment. Contrary to some earlier estimates, the thermal loads were significant, and it was not possible to operate for more than 3 s without water cooling. It is not clear if this was because of periodic detonation failures and consequent deflagrative modes of combustion as reported in some earlier studies.

The work reported in the open literature and discussed earlier has focused on gaseous fuels. However, for volume-limited propulsion applications, PDEs operating on liquid fuels need to be demonstrated. In a recent study, Brophy et al.[92] reported on experiments using JP-10/oxygen and JP-10/air aerosols. The fuel–oxygen mixture was successfully detonated to obtain an engine operating at 5 Hz, but the tests with the fuel–air mixture were not successful.

Computational studies continue to make progress in the study of the PDE.[87,93–97] The effect of nozzle shapes and incomplete transition to C–J detonations have been studied by Eidelman and Yang.[87] They find that the cycle efficiency will be virtually the same whether a C–J detonation wave is initiated instantaneously or if the C–J value is attained only at the end of the detonation chamber. Primarily based on this study,[87] they come to an interesting conclusion that "initiation energies that are required for PDE operations can be small and comparable to energies required for initiation of (other) combustion processes." However, this is yet to be substantiated experimentally. Sekar et al.[93] reexamine open- and closed-end initiation and the basic self-aspirating configuration of Eidelman[8] using more recent computational tools. Injection and mixing issues that have generally been ignored in previous numerical studies are also beginning to be addressed.[94] Both front-wall and lateral-wall injections were studied, and the time required for fuel injection was estimated. It is suggested that it may be possible to fill only a portion of the chamber during high-frequency operations. Recent computational studies also suggest that preconditioning the fuel–air mixture using a shock wave can significantly reduce the DDT distance.[95] The performance estimates mentioned throughout the discussion of the PDE show significant variation. A systematic review of various performance estimates and possible reasons for the observed variation have been presented.[96,97] These numerical studies suggest that the time history of the back pressure is a crucial parameter affecting the estimated performance.

Other Detonation Engines

There have also been several other interesting conceptual studies on the applications of detonations to engines. Cambier et al.[98] have proposed a pulsed-detonation wave augmentation device as part of a hybrid engine for a single-stage-to-orbit airbreathing hypersonic vehicle. Here the PDE is used for both thrust generation as well as for mixing/combustion augmentation. Two specific configurations were investigated numerically.

The concept of a detonation internal combustion engine was proposed by Loth and Loth[99] and Loth.[100] Here, a conventional piston cylinder configuration is modified to incorporate a separate detonation chamber, which is isolated by a valve from the compression chamber during fuel injection and discharges tangentially into a vortex chamber formed by the piston and cylinder at top dead center. The rapid detonative combustion is followed by rapid dilution through mixing with air in the vortex chamber to reduce the formation of NO_x and unburned hydrocarbons and to achieve an overall lean mixture. The vortex chamber was also designed to store a portion of the detonation wave's kinetic energy. Overall thermal efficiencies somewhat better than constant volume combustion were postulated under ideal conditions.

Conclusions

Detonation waves have been explored extensively for propulsion applications because of their inherent theoretical advantage over deflagrative combustion. However, practical developments to date have been of idealized systems or laboratory-scale devices or both. The basic ideas behind most of the current systems being investigated have been known for a while, but still many of the details need to be understood. Advances in computations and experimental diagnostics appear to be poised to make practical propulsion devices based on detonation waves a reality.

Two major systems currently under development are the ram accelerator and the PDE. In both cases, the theoretical and computational studies have been far more encouraging than the experiments. However, in both cases, actual demonstrations of devices working on gaseous fuels have taken place. In the case of the ram accelerator, fuel–oxygen–diluent mixtures have been used, and the primary problem appears to be heat transfer and related material failures. The use of gaseous fuels is not a major issue here, but new materials for the projectiles need to be explored.

In the case of the PDE, most of the successful operations have been with fuel–oxygen mixtures. There still has not been a direct comparison between detailed experimental data and related theoretical and computational results. Furthermore, most of the PDE and related work to date have focused on gaseous mixtures. PDEs operating on multiphase mixtures need to be emphasized because it would be more practical to use liquid fuels for most of the propulsion applications proposed for these systems. There are several other general issues that need to be resolved. Clearly, the evacuation of exhaust gases is important both from the point of view of controlling the cycle time and for preventing autoignition and mixing with fresh gases. The heat transfer and noise from PDEs have also not been reported in any detail. Other issues include inlet–combustor and combustor–nozzle interactions, and scalability of the entire device.

Acknowledgments

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References

[1]Fickett, W., and Davis, W. C., *Detonation*, Univ. of California Press, Berkeley, CA, 1979.

[2]Hoffmann, N., "Reaction Propulsion by Intermittent Detonative Combustion," German Ministry of Supply, AI152365 Volkenrode Translation, 1940 (cited in Ref. 16).

[3]Roy, M., "Propulsion par Statoreacteur a Detonation," *Comptes-Rendus de l'Academie des Sciences*, Vol. 222, 1946, pp. 31, 32.

[4]Dabora, E. K., and Broda, J. C., "Standing Normal Detonations and Oblique Detonations for Propulsion," AIAA Paper 93-2325, July 1993.

[5]Dabora, E. K., "Status of Gaseous Detonation Waves and Their Role in Propulsion," *Fall Technical Meeting of the Eastern States Section of the Combustion Institute*, Combustion Inst., Pittsburgh, PA, 1994, pp. 11–18.

[6]Rubins, P. M., and Bauer, R. C., "Review of Shock-Induced Supersonic Combustion Research and Hypersonic Applications," *Journal of Propulsion and Power*, Vol. 10, No. 5, 1994, pp. 593–601.

[7]Eidelman, S., Grossmann, W., and Lottati, I., "Review of Propulsion Applications and Numerical Simulations of the Pulsed Detonation Engine Concept," *Journal of Propulsion and Power*, Vol. 7, No. 6, 1991, pp. 857–865; also AIAA Paper 89-2446, July 1989.

[8]Eidelman, S., and Grossmann, W., "Pulsed Detonation Engine: Experimental and Theoretical Review," AIAA Paper 92-3168, July 1992.

[9]Reingold, L., "Recherches sur les combustions permanentes apportees aux foyers a circulation interne supersonique," ONERA, TN2, Dept. of Energy and Propulsion, Study 728-E, Paris, March 1950.

[10]Bitondo, D., and Bollay, W., "Preliminary Performance Analysis of the Pulse-Detonation-Jet Engine System," Aerophysics Development Corp., Rept. ADC-102-1, April 1952.

[11]Gross, R. A., "Exploratory Study of Combustion in Supersonic Flow," U.S. Air Force Office of Scientific Research, TN 59-587, Washington, DC, June 1959.

[12]Gross, R. A., and Chinitz, W., "A Study of Supersonic Combustion," *Journal of Aerospace Science*, Vol. 27, No. 7, 1960, pp. 517–525.

[13]Nicholls, J. A., Dabora, E. K., and Gealer, R. L., "Studies in Connection with Stabilized Gaseous Detonation Waves," *Seventh Symposium (International) on Combustion*, Combustion Inst., Pittsburgh, PA, 1959, pp. 766–772.

[14]Nicholls, J. A., and Dabora, E. K., "Recent Results on Standing Detonation Waves," *Eighth Symposium (International) on Combustion*, Combustion Inst., Pittsburgh, PA, 1962, pp. 644–655.

[15]Dunlap, R., Brehm, R. L., and Nicholls, J. A., "A Preliminary Study of the Application of Steady-State Detonative Combustion to a Reaction Engine," *Jet Propulsion*, Vol. 28, No. 7, 1958, pp. 451–456.

[16]Nicholls, J. A., Wilkinson, H. R., and Morrison, R. B., "Intermittent Detonation as a Thrust-Producing Mechanism," *Jet Propulsion*, Vol. 27, No. 5, 1957, pp. 534–541.

[17]Krzycki, L. J., "Performance Characteristics of an Intermittent Detonation Device," U.S. Naval Ordnance Test Station, U.S. Naval Weapons Rept. 7655, China Lake, CA, 1962.

[18]Nicholls, J. A., Cullen, R. E., and Ragland, K. W., "Feasibility Studies of a Rotating Detonation Wave Rocket Motor," *Journal of Spacecraft and Rockets*, Vol. 3, No. 6, 1966, pp. 893–898.

[19]Adamson, T. C., and Olsson, G. R., "Performance Analysis of a Rotating Detonation Wave Rocket Engine," *Astronautica Acta*, Vol. 13, No. 4, 1967, pp. 405–415.

[20]Shen, P. I., and Adamson, T. C., "Theoretical Analysis of a Rotating Two-Phase Detonation in Liquid Rocket Motors," *Astronautica Acta*, Vol. 17, No. 4, 1972, pp. 715–728.

[21]Clayton, R. M., and Rogero, R. S., "Experimental Measurements on a Rotating Detonation-Like Wave Observed During Liquid Rocket Resonant Combustion," Jet Propulsion Lab., TR 32-788, California Inst. of Technology, Pasadena, CA, Aug. 1965.

[22]Back, L. H., "Application of Blast Wave Theory to Explosive Propulsion," *Acta Astronautica*, Vol. 2, 1975, pp. 391–407.

[23]Varsi, G., Back, L. H., and Kim, K., "Blast Wave in a Nozzle for Propulsion Applications," *Acta Astronautica*, Vol. 3, 1976, pp. 141–156.

[24]Kim, K., Varsi, G., and Back, L. H., "Blast Wave Analysis for Detonation Propulsion," *AIAA Journal*, Vol. 10, No. 10, 1977, pp. 1500–1502.

[25]Back, L. H., Dowler, W. L., and Varsi, G., "Detonation Propulsion Experiments and Theory," *AIAA Journal*, Vol. 21, No. 10, 1983, pp. 1418–1427.

[26]Kantrowitz, A., "Propulsion to Orbit by Ground Based Lasers," *Astronautics and Aeronautics*, Vol. 10, No. 5, 1972, p. 74.

[27]Hyde, R. A., "One-D Modelling of a Two-Pulse LSD Thruster," *Proceedings of the 1986 SDIO/DARPA Workshop on Laser Propulsion*, edited by J. T. Kare, Lawrence Livermore National Labs., 1987, pp. 79–88.

[28]Emery, M. H., Kailasanath, K., Oran, E. S., and Gardner, J. H., "Computational Studies of Laser Supported Detonations," *Proceedings of the 1987 SDIO Workshop on Laser Propulsion*, edited by J. T. Kare, Lawrence Livermore National Labs., 1990, pp. 43–55.

[29]Emery, M. H., Kailasanath, K., and Oran, E. S., "Numerical Simulations of Laser Supported Detonations," 1988 SDIO Workshop on Laser Propulsion, Lawrence Livermore National Labs., April 1988.

[30]Carrier, G. F., Fendell, F., McGregor, D., Cook, S., and Vazirani, M., "Laser-Initiated Conical Detonation Wave for Supersonic Combustion," AIAA Paper 91-0578, Jan. 1991.

[31]Fendell, F. E., Mitchell, J., McGregor, R., Magiawala, K., and Sheffield, M., "Laser-Initiated Conical Detonation Wave for Supersonic Combustion. II," AIAA Paper 92-0088, Jan. 1992.

[32]Carrier, G. F., Fendell, F. E., and Chou, M. S., "Laser-Initiated Conical Detonation Wave for Supersonic Combustion. III," AIAA Paper 92-3247, July 1992.

[33]Menees, G. P., Adelman, H. G., Cambier, J.-L., and Bowles, J. V., "Wave Combustors for Trans-Atmospheric Vehicles," *Journal of Propulsion and Power*, Vol. 8, No. 3, 1992, pp. 709–713.

[34]Cambier, J. L., Adelman, H., and Menees, G., "Numerical Simulations of an Oblique Detonation Wave Engine," AIAA Paper 88-0063, 1988.

[35]Atamanchuk, T., and Sislian, J., "On- and Off-design Performance Analysis of Hypersonic Detonation Wave Ramjets," AIAA Paper 90-2473, 1990.

[36]Kuznetsov, M. M., Neyland, V. J., and Sayapin, G. N., "Efficiency Investigation of Scramjet with Detonation and Shockless Supersonic Combustion," *Utchenye Zapisky TsAGI*, Vol. 23, No. 2, 1992, pp. 30–37.

[37]Bruckner, A. P., and Hertzberg, A., "Ram Accelerator Direct Launch System for Space Cargo," International Astronautical Federation, Paper 87-211, 1987.

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

[39]Kull, A., Burnham, E., Knowlen, C., Bruckner, A. P., and Hertzberg, A., "Experimental Studies of the Superdetonative Ram Accelerator Modes," AIAA Paper 89-2632, 1989.

[40]Patz, G., Seiler, F., Smeets, G., and Srulijes, J., "Status of ISL's RAMAC30 with Fin Guided Projectiles Accelerated in a Smooth Bore," *Proceedings of the Second International Workshop on Ram Accelerators*, Univ. of Washington, Seattle, WA, 1995.

[41]Seiler, F., Patz, G., Smeets, G., and Srulijes, J., "Gasdynamic Limits of Ignition and Combustion of a Gas Mixture in ISL's RAMAC30 Scram Accelerator," *Proceedings of the Second International Workshop on Ram Accelerators*, Univ. of Washington, Seattle, WA, 1995.

[42]Seiler, F., Patz, G., Smeets, G., and Srulijes, J., "Influence of Projectile Material and Gas Composition on Superdetonative Combustion in ISL's RAMAC30," AIAA Paper 98-3445, July 1998.

[43]Brackett, D. C., and Bogdanoff, D. W., "Computational Investigation of Oblique Detonation Ramjet-in-Tube Concepts," *Journal of Propulsion and Power*, Vol. 5, No. 3, 1989, pp. 276–281.

[44]Yungster, S., Eberhardt, S., and Bruckner, A. P., "Numerical Simulation of Shock-Induced Combustion Generated by High-Speed Projectiles in Detonable Gas Mixtures," AIAA Paper 89-0673, 1989.

[45]Rom, J., and Kivity, Y., "Accelerating Projectiles Up to 12 km/s Utilizing the Continuous Detonation Propulsion Method," AIAA Paper 88-2969, 1988.

[46]Humphrey, J. W., "Parametric Study of an ODW Scramaccelerator for Hypersonic Test Facilities," AIAA Paper 90-2470, 1990.

[47]Yungster, S., "Navier–Stokes Simulation of the Supersonic Combustion Flowfield in a Ram Accelerator," AIAA Paper 91-1916, 1991.

[48]Li, C., Kailasanath, K., Oran, E. S., Boris, J. P., Paper and Landsberg, A. M., "Numerical Simulations of Transient Flows in Ram Accelerators," AIAA Paper 93-1916, 1993.

[49]Li, C., Kailasanath, K., Oran, E. S., Landsberg, A. M., and Boris, J. P., "Dynamics of Oblique Detonations in Ram Accelerators," *Shock Waves*, Vol. 5, June 1995, pp. 97–101.

[50]Yungster, S., and Radhakrishnan, K., "Computational Study of Flow Establishment in a Ram Accelerator," AIAA Paper 98-2489, July 1995.

[51]Choi, J. Y., Jeung, I.-S., and Yoon, Y., "Numerical Study of Scram Accelerator Starting Characteristics," *AIAA Journal*, Vol. 36, No. 6, 1998, pp. 1029–1038.

[52]Bezgin, L., Ganzhelo, A., Gouskov, O., and Kopchenov, V., "Some Numerical Investigation Results of Shock-Induced Combustion," *Proceedings of the AIAA 8th International Space Planes and Hypersonic Systems and Technologies Conference*, AIAA, Reston, VA, 1998, pp. 72–82.

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

[54]Fujiwara, T., Matsuo, A., and Nomoto, H., "Two-Dimensional Detonation Supported by a Blunt Body or a Wedge," AIAA Paper 88-0089, Jan. 1988.

[55]Fan, B. C., Sichel, M., and Kauffman, C. W., "Analysis of Oblique Shock-Detonation Wave Interactions in the Supersonic Flow of a Combustible Medium," AIAA Paper 88-0441, Jan. 1988.

[56]Dabora, E. K., Desbordes, D., Guerraud, C., and Wagner, H. G., "Oblique Detonations at Hypersonic Velocities," *Dynamics of Detonations and Explosions: Detonations*, Vol. 133, Progress in Astronautics and Aeronautics, AIAA, Washington, DC, 1990, pp. 187–201.

[57]Li, C., Kailasanath, K., and Oran, E. S., "Stability of Oblique Detonations in Ram Accelerators," AIAA Paper 92-0089, Jan. 1992.

[58]Li, C., Kailasanath, K., and Oran, E. S., "Structure of Reaction Waves Behind Oblique Shocks," *Dynamic Aspects of Detonation*, Vol. 153, Progress in Astronautics and Aeronautics, AIAA, Washington, DC, 1993, pp. 231–240.

[59]Li, C., Kailasanath, K., and Oran, E. S., "Detonation Structures Behind Oblique Shocks," *Physics of Fluids*, Vol. 6, April 1994, pp. 1600–1611.

[60]Da Silva, L. F., and Deshaies, B., "Numerical Study of Some Ignition Regimes of Combustible Supersonic Flows over a Wedge," *Proceedings of Second International Workshop on Ram Accelerators*, Paper 15, Univ. of Washington, Seattle, WA, 1995.

[61]Thaker, A. A., and Chelliah, H. K., "Numerical Prediction of Oblique Detonation Wave Structures Using Detailed and Reduced Reaction Mechanisms," *Combustion Theory and Modelling*, Vol. 1, No. 4, 1997, pp. 347–376.

[62]Desbordes, D., Guerraud, C., and Hamada, L., "Supersonic H2-Air Combustions Behind Oblique Shock Waves," 14th International Colloquium on Dynamics of Explosions and Reactive Systems, Paper D2.8, Univ. of Coimbra, Portugal, Aug. 1993.

[63]Li, C., Kailasanath, K., and Oran, E. S., "Detonation Structures Generated by Multiple Shocks on Ram-Accelerator Projectiles," *Combustion and Flame*, Vol. 108, 1997, pp. 173–186.

[64]Viguier, C., and Desbordes, D., "Conditions of Onset and Stabilization of Oblique Detonation Waves," *Advances in Experimentation and Computation of Detonations*, edited by G. D. Roy, S. H. Frolov, K. Kailasanath, and N. Smirnov, ENAS, Moscow, 1998, pp. 40, 41.

[65]Bussing, T., and Pappas, G., "Introduction to Pulse Detonation Engines," AIAA Paper 94-0263, 1994.

[66]Helman, D., Shreeve, R. P., and Eidelman, S., "Detonation Pulse Engine," AIAA Paper 86-1683, June 1986.

[67]Cambier, J. L., and Adelman, H. G., "Preliminary Numerical Simulations of a Pulsed Detonation Wave Engine," AIAA Paper 88-2960, July 1988.

[68]Eidelman, S., Grossmann, W., and Lottati, I., "Air-Breathing Pulsed Detonation Engine Concept: A Numerical Study," AIAA Paper 90-2420, July 1990.

[69]Eidelman, S., Grossmann, W., and Lottati, I., "Computational Analysis of Pulsed Detonation Engines and Applications," AIAA Paper 90-0460, Jan. 1990.

[70] Lynch, E. D., Edelman, R., and Palaniswamy, S., "Computational Fluid Dynamic Analysis of the Pulse Detonation Engine Concept," AIAA Paper 94-0264, Jan. 1994.

[71] Lynch, E. D., and Edelman, R. B, "Analysis of Flow Processes in the Pulse Detonation Wave Engine," AIAA Paper 94-3222, June 1994.

[72] Bussing, T., Hinkey, J. B., and Kaye, L., "Pulse Detonation Engine Preliminary Design Considerations," AIAA Paper 94-3220, June 1994.

[73] Zitoun, R., Gamezo, V., Guerraud, C., and Desbordes, D., "Experimental Study on the Propulsive Efficiency of Pulsed Detonation," 21st International Symposium on Shock Waves, Paper 8292, Great Keppel Island, Australia, July 1997.

[74] Sterling, J., Ghorbanian, K., Humphrey, J, and Sobota, T., "Numerical Investigations of Pulse Detonation Wave Engines," AIAA Paper 95-2479, July 1995.

[75] Hinkey, J. B., Bussing, T. R. A., and Kaye, L., "Shock Tube Experiments for the Development of a Hydrogen-Fueled Pulse Detonation Engine," AIAA Paper 95-2578, July 1995.

[76] Schelkin, K. L., *Soviet Journal of Technical Physics*, Vol. 10, 1940, pp. 823–827.

[77] Bussing, T. R. A., "A Rotary Valve Multiple Pulse Detonation Engine (RVMPDE)," AIAA Paper 95-2577, July 1995.

[78] Bratkovich, T. E., and Bussing, T. R. A., "A Pulse Detonation Engine Performance Model," AIAA Paper 95-3155, July 1995.

[79] Ting, J. M., Bussing, T. R. A., and Hinkey, J. B., "Experimental Characterization of the Detonation Properties of Hydrocarbon Fuels for the Development of a Pulse Detonation Engine," AIAA Paper 95-3154, July 1995.

[80] Stanley, S. B., Burge, K., and Wilson, D., "Experimental Investigation of Pulse Detonation Wave Phenomenon as Related to Propulsion Application," AIAA Paper 95-2580, July 1995.

[81] Eidelman, S., Yang, X., and Lottati, I., "Pulsed Detonation Engine: Key Issues," AIAA Paper 95-2754, July 1995.

[82] Aarnio, M. J., Hinkey, J. B., and Bussing, T. R. A., "Multiple Cycle Detonation Experiments During the Development of a Pulse Detonation Engine," AIAA Paper 96-3263, July 1996.

[83] Pegg, R. J., Couch, B. D., and Hunter, L. G., "Pulse Detonation Engine Air Induction System Analysis," AIAA Paper 96-2918, July 1996.

[84] Sterling, J., Ghorbanian, K., and Sobota, T., "Enhanced Combustion Pulsejet Engines for Mach 0 to 3 Applications," AIAA Paper 96-2687, July 1996.

[85] Cambier, J. L., and Tegner, J. K., "Strategies for PDE Performance Optimization," AIAA Paper 97-2743, July 1997.

[86] Stuessy, W. S., and Wilson, D. R., "Influence of Nozzle Geometry on the Performance of a Pulse Detonation Engine," AIAA Paper 97-2745, July 1997.

[87] Eidelman, S., and Yang, X., "Analysis of the Pulse Detonation Engine Efficiency," AIAA Paper 98-3877, 1998.

[88] Hinkey, J. B., Williams, J. T., Henderson, S. E., and Bussing, T. R. A., "Rotary-Valved, Multiple-Cycle, Pulse Detonation Engine Experimental Demonstration," AIAA Paper 97-2746, July 1997.

[89] Bussing, T. R. A., Bratkovich, T. E., and Hinkey, J. B., "Practical Implementation of Pulse Detonation Engines," AIAA Paper 97-2748, July 1997.

[90] Bratkovich, T. E., Aamio, M. J., Williams, J. T., and Bussing, T. R. A., "An Introduction to Pulse Detonation Rocket Engines (PDREs)," AIAA Paper 97-2742, July 1997.

[91] Hinkey, J. B., Henderson, S. E., and Bussing, T. R. A., "Operation of a Flight-Scale Rotary-Valved, Multiple-Combustor, Pulse Detonation Engine (RVMPDE)," AIAA Paper 98-3881, July 1998.

[92] Brophy, C., Netzer, D., and Forster, D., "Detonation Studies of JP-10 with Oxygen and Air for Pulse Detonation Engine Development," AIAA Paper 98-4003, July 1998.

[93] Sekar, B., Palaniswamy, S., Peroomian, O., and Chakravarthy, S., "A Numerical Study of the Pulse Detonation Wave Engine with Hydrocarbon Fuels," AIAA Paper 98-3880, July 1998.

[94] Musielak, D. E., "Injection and Mixing of Gas Propellants for Pulse Detonation Propulsion," AIAA Paper 98-3878, July 1998.

[95] Sjogreen, B., and Tegner, J., "Mechanisms Governing Detonation Waves and Their Initiation—Implications on the Pulse Detonation Engine," AIAA Paper 99-IS-134, Sept. 1999.

[96] Kailasanath, K., Patnaik, G., and Li, C., "Computational Studies of Pulse Detonation Engines: A Status Report," AIAA Paper 99-2634, June 1999.

[97] Kailasanath, K., and Patnaik, G., "Pulsed Detonation Engines—What is Its Performance?," *Proceedings of the 36th JANNAF Combustion Meeting*, Chemical Propulsion Information Agency, Laurel, MD, 1999.

[98] Cambier, J. L., Adelman, H. G., and Menees, G. P., "Numerical Simulations of a Pulsed Detonation Wave Augmentation Device," AIAA Paper 93-1985, June 1993.

[99] Loth, E., and Loth, J. L., "High Efficiency Detonation Internal Combustion Engines," AIAA Paper 92-3171, July 1992.

[100] Loth, E., "Vortex Formation in a Proposed Detonation Internal Combustion Engine," *Journal of Propulsion and Power*, Vol. 11, No. 3, 1995.

M. Sichel
Associate Editor