AIAA Journal
Vol. 41, No. 2, February 2003

Recent Developments in the Research on Pulse Detonation Engines

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

Introduction

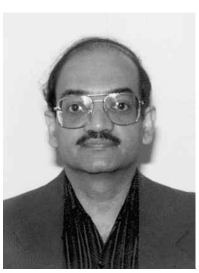
IN principle, detonations are an extremely efficient means of combusting a fuel-oxidizer mixture and releasing its chemical energy content. During the past 60 years or so, there have been numerous research efforts at harnessing the potential of detonations for propulsion applications.[1] There is a renewed interest lately on intermittent or pulsed detonations engines. Eidelman et al.[2] and Eidelman and Grossmann[3] have reviewed some of the initial research as well as work done in the late 1980s on pulse detonation engines (PDEs). The basic theory, design concepts, and the work in the early 1990s related to pulse detonation engines have been discussed by Bussing and Pappas.[4] The focus of a more recent review[5] is on performance estimates from various experimental, theoretical and computational studies. More recently, work related to nozzles for PDEs has been discussed.[6] Other reviews[7–9] discussing the objectives and accomplishments of various programs are also available. The objective of this paper is to update the previous reviews, focusing on the more recent developments in the research on PDEs. The review is restricted to work openly available in the literature but includes ongoing efforts around the world.

Currently, there are several programs sponsored by Office of Naval Research (ONR), U.S. Air Force, NASA, Defense Advanced Research Projects Agency, and other agencies in the United States as well as several parallel efforts in Belarus, Canada, France, Japan, Russia, Sweden, and other countries. The results from some of these programs are just beginning to be published. A summary of recent progress and the various organizations and people involved in PDE research in Japan has been presented.[9] Reports of the basic PDE research sponsored by ONR are available in the proceedings of a recurring annual meeting (for example, see Ref. 10). Recent work conducted outside the United States has been reported at international meetings on detonations such as those held in Seattle[11] (for more information, see http://www.engr.washington.edu/epp/icders/) and Moscow.[12] Although an attempt is made to cover a broad range of the reported research, the shear volume of papers presented with PDEs in the title make it impractical to be exhaustive.

Rather than providing a chronological report, an attempt is made here to discuss the recent progress in terms of broad topic areas. The key issues that need to be resolved have been addressed in a number of papers (e.g., Refs. 13 and 14). The specific order in which to discuss the various topics was determined by considering the schematic of an idealized, laboratory pulse detonation engine shown in Fig. 1. This idealized engine is representative of the device used in many of the recent experimental and computational studies and consists of a tube closed at one end and open at the other. Typically, fuel and oxidizer are injected and mixed near the head end to achieve a nearly homogeneous mixture and ignited. Depending on the mixture and ignition energies involved, a detonation, which travels towards the open end of the tube leaving behind a high-pressure, high-temperature gas that generates thrust as it expands and leaves the tube, might-form. The first topic discussed covers the injection and atomization of liquid fuels and fuel-air mixing. Even if the fuel and air are premixed, rapid deposition of energy into the mixture does not necessarily mean that a detonation wave will be formed. Issues involved and recent successes in the initiation of detonations are addressed next. Developments in diagnostics and computations of the detonation wave are then briefly discussed as they provide a good characterization of the pressure, temperature, and velocity flowfields within the tube. This leads to the issue of the performance of pulse detonation engines. The performance of idealized laboratory pulse detonation engines has received significant attention recently, and, as this review will show, it is one of the topics that appears to be resolved. However, the performance of these devices at flight conditions is still a controversial topic. This is partly because of the uncertainty concerning the "proper" design of nozzles and inlets for these engines. Nozzles for the PDE present challenging design and integration issues because of the inherently unsteady nature of the pulse detonation process. For a high-frequency, multitube system, where the overall system might appear to be nearly steady, there are issues in designing a common flow path for the exhaust from the individual thrust tubes. Issues concerning global performance estimation and the results from recent analysis of some of the applications proposed for the PDE are also presented. It is hoped that this review provides a clearer picture of our current understanding and highlights the need for additional research on PDEs.

Atomization and Fuel–Oxidizer Mixing

Detonations are essentially a premixed combustion process. The well-known detonation parameters such as the Chapman–Jouguet (CJ) velocities and CJ pressures are derived with the implicit assumption of a perfectly mixed fuel–oxidizer or fuel–air mixture. The importance of adequately mixing the fuel and oxidizer was highlighted by the experimental investigations of Stanley et al.,[15] who obtained very low sub-CJ velocities when injecting the fuel and oxidizer at different times and not invoking additional measures to



K. Kailasanath is currently the Head of the Center for Reactive Flow and Dynamical Systems (Code 6410) at the Naval Research Laboratory. He received his Ph.D. from the Georgia Institute of Technology in 1980 and has been at the Naval Research Laboratory since then. Prior to that, he received his M.S.A.E. from the Georgia Institute of Technology in 1979 and his B.Tech. in aeronautical engineering from the Indian Institute of Technology (Madras) in 1976. His research interests include multiphase flow physics; the structure, stability, and dynamics of flames, fires, and detonations; combustion instabilities in ramjets; subsonic and supersonic mixing and noise generation; and the simulation of advanced propulsion system concepts. He has published over 200 papers on these topics. He is a Fellow of the Institute of Physics and an Associate Fellow of the AIAA. He was an Associate Editor of the *AIAA Journal* (1995–2000) and is currently on the board of the journal *Combustion Theory and Modeling*. He is a past Chair of the AIAA Propellants and Combustion Technical Committee. E-mail: kailas@lcp.nrl.navy.mil.

Received 23 April 2002; revision received 8 August 2002; accepted for publication 2 October 2002.

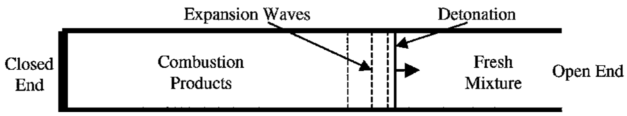


Fig. 1 Schematic of an idealized, laboratory pulse detonation engine.

ensure that they were well mixed. The use of turbulence-producing devices appeared to significantly improve the mixing and the attainment of higher velocities but also resulted in significant thrust losses.

In the more recent studies[16–18] cavities, blockages, and jet impingement are some of the techniques used to enhance fuel–air mixing. Fuel injection and mixing considerations that have generally been ignored in most numerical studies are also beginning to be addressed.[19,20] Very good results during multicycle operation are obtained if the mixing issue is isolated by premixing before injection into the detonation chamber.[21] Even in this case, the interaction between the burned gases generated in one cycle with the fresh premixed mixture injected in a subsequent cycle could lead to premature ignition. Mixing under flight conditions is an issue that has not been addressed adequately in the open literature.

For many practical volume limited applications there is a need to use liquid fuels. The difficulties already mentioned in the mixing of gaseous fuels and oxidizers are compounded when considering liquid fuels. To begin, additional issues such as atomization and uniformity of fuel–air distribution must be addressed. Lasheras et al.[22] discuss atomization by a high-speed coaxial airflow. The system they have designed operates with a small air pressure drop and still provides very small droplets. Atomization under pulsatile or transient conditions was shown to be nearly identical to steady-state atomization behavior. The air-intake process must ensure sufficiently large stagnation pressures to drive the high-speed flows necessary to atomize the injected fuel. They indicate that for gas-injection velocities greater than 220 m/s Sauter mean diameter (SMD) values below 10 μ can be achieved. Further reductions of droplet sizes are possible with the addition of swirl, which also helps to tailor the radial and axial fuel distribution. They also suggest that "droplet atomization and vaporization behind the strong leading shock of a detonation wave is sufficiently rapid, through known shock-induced instabilities of the liquid, that the droplet response in a JP-10 spray is unlikely to be a critical factor that promotes detonation failure."[22] Ignition requirements are likely to be more critical. Ignition occurs in the gas phase, and the vapor pressure of the liquid must be sufficiently high for the gas to be ignitable and detonable.

Detonation Initiation

Reliable and repeated low-energy initiation of detonations in the high-speed flow in pulse detonation engines operating on practical mixtures is one of the most challenging problems in the development of these engines. Significant research efforts and accomplishments continue to be made on this topic. The power and energy required for direct initiation of a detonation has been investigated extensively both experimentally and numerically (e.g., Refs. 23 and 24). The amount of energy required and the rate at which it needs to be deposited (power) to initiate detonations in hydrocarbon–air (other than acetylene) mixtures is impractical.[25] On a fundamental level the critical energy for direct initiation and minimum chamber for propagation are closely correlated to the detonation cell size. For stoichiometric hydrocarbon–air mixtures the detonation cell size increases from about 9 mm for acetylene–air to over 300 mm for methane-air.[26] Therefore, alternate means of initiating a detonation must be considered. If the energy input is insufficient for direct initiation, a flame can be generated, and under appropriate conditions a high-speed flame or deflagration could transition to a detonation in a process called deflagration to detonation transition (DDT). Therefore, many of the studies on detonation initiation in PDEs have focused on DDT.

There have been far too many fundamental studies of DDT to discuss adequately in this paper; only those recent works that have linked their work to PDEs are discussed here. Sinibaldi et al.[27] investigated the dependence of the DDT transition distance on parameters such as ignition energy, ignition location, and mixture stoichiometry. In general, there was little or no dependence on ignition energy once it was above a minimum. Placing the ignitor slightly away from the wall helped, but if it was too far away the transition lengths were longer. A drastic increase in DDT lengths was found when the equivalence ratio ϕ was less than 0.75 in the ethylene–oxygen–nitrogen mixtures. On the rich side there was a much less drastic change in transition lengths. Even with a tube length of 75 in. (1905 mm), DDT did not occur in many of the mixtures investigated. Previous studies have indicated that the distance required for DDT could be large compared to the tube dimensions,[28] even for hydrogen-air mixtures.[29] Therefore, means of reducing the DDT distance have been investigated.

A classical approach is that from Shchelkin,[30] where a spiral is introduced into the tube to promote the transition to detonation. For example, Schauer et al.[21] placed a Shchelkin spiral in the first 12-in. (305-mm) section of a 36-in. (915-mm) tube and found consistent transition to detonation during multicycle operation using hydrogen–air mixtures. Without the spiral, transition occurred only towards the end of the tube. Shchelkin spirals are also being used to initiate detonations in ethylene–air mixtures.[16,31] Other approaches to enhance DDT include the use of physical obstacles other than spirals (various shaped blockages, orifice plates, etc.) and chemical promoters such as fuel additives and fuel blends.

Lee et al.[32] conducted a parametric study where the blockage ratio, spacing between obstacles, and the length of the tube section with obstacles were varied. They conducted both single-shot and multicycle experiments. In their single-shot experiments circular, flat-plate obstacles were placed in a helical arrangement (Fig. 2) in a 45-mm square tube having a length of 1650 mm. The tube was filled with an ethylene–air mixture. OH planar laser induced fluorescence (PLIF) and schlieren imaging showed that the obstacles generated large-scale turbulence and enhanced flame acceleration. Localized explosion of pockets of unburned mixture further enhanced the flame speed. They found that the obstacles must accelerate the flame to at least half the CJ speed for transition to detonation. Blockage ratios between 0.3 and 0.6 were found to provide optimum levels of flame stretching without excessive flow drag. This is consistent with the observation of Lindstedt and Michels[28] that a blockage ratio of 0.44 is optimal for DDT. A further reduction in the DDT time by 50% was observed during multicycle operation when compared to the single-shot experiments.[33]

Cooper et al.[34] has shown that DDT time can be reduced by an average of 65% (Fig. 3) in various propane and ethylene–oxygen–nitrogen mixtures using obstacles with a blockage ratio of 0.43. Use of various obstacles could also extend the nitrogen dilution from 30 to 60%. However, they also note that the obstacles can reduce the impulse by up to 25%. If obstacles are not used, there seems to be little difference in impulse whether the detonation occurs as a result of either direct initiation or DDT.[35,36] In the work of Harris et al.,[35] stoichiometric propane–oxygen mixtures having various amounts of nitrogen dilution were initiated both directly and also using a weak spark to study the effect of DDT distance on performance. A significant difference in impulse was not observed as long as the DDT occurred within the tube and no mixture was spilled prior to detonation. The time for delivery of the impulse was 1.5 times longer with DDT; hence, the average thrust was lower. The reason for still attaining similar impulse appears to be the presence of a

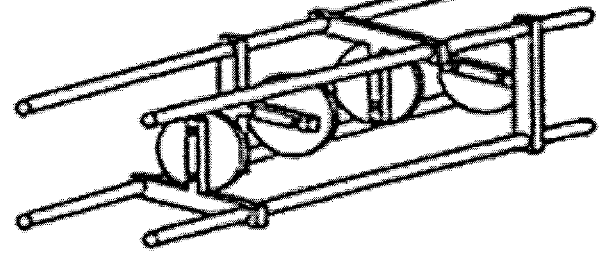


Fig. 2 Schematic of the obstacle configuration used by Lee et al.[32] to enhance DDT.

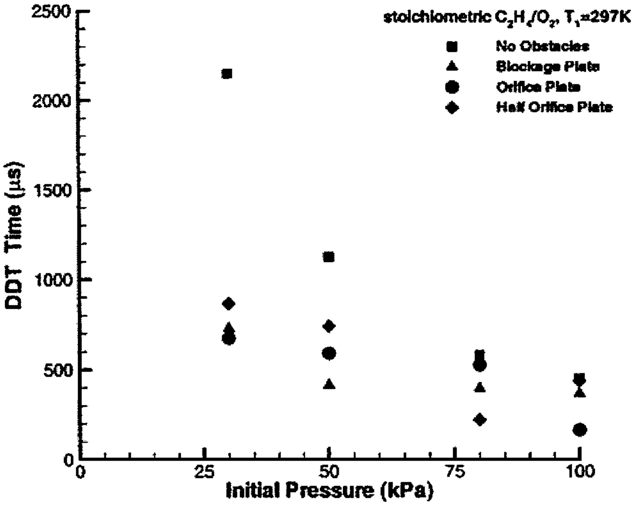


Fig. 3 Effect of three obstacle configurations on measured DDT time in a 76-mm-diam tube of L/d = 13 (from Cooper et al.[34]).

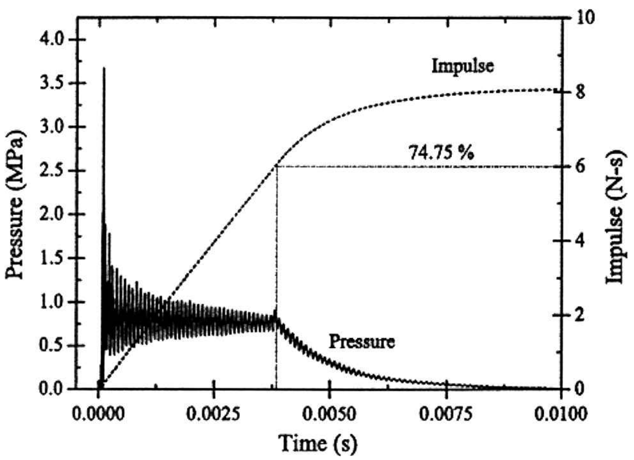


Fig. 4 Pressure and pressure-based impulse after direct initiation of a detonation in a propane–oxygen–nitrogen mixture (from Harris et al.[35]).

retonation wave that further compresses the burned mixture and raises the pressure. As seen in Figs. 4 and 5, taken from Harris et al.,[35] the actual pressure history curves are quite different depending on the method of initiation. Nearly 75% of the impulse is achieved by the time the expansion wave reaches the closed end in direct initiation, but only about 39% of the impulse is attained before the arrival of the retonation wave. If impulse is measured up to the time that the pressure reaches the corresponding point during DDT, nearly 71% of the impulse is obtained. This result is encouraging from a fundamental point of view and is similar to an observation made earlier by Eidelman and Yang[37] that the computed PDE performance was not affected as long as the detonation occurred somewhere within the tube. In practical applications, the impulse with DDT is likely to be lower because of the use of obstacles or other transition-enhancement devices.[34]

Another approach to reducing the DDT distance is the use of additives. Akbar et al.[38] report on the effect of nitrate sensitizers used with prevaporized JP-10 and Jet A/air mixtures. They find that it was not possible to greatly sensitize these mixtures using small amounts of the nitrates because the cell widths of the nitrates were comparable to those of the main mixtures. As mentioned before, the cell sizes are strongly correlated to difficulty to initiate detonations. The use of fuel blends[39] and dual fuels[40] are also being considered. The fuels should exhibit different reactivity in terms of ignition delays, burning rates, and sensitivity to detonation. Jet propulsion kerosene and hydrogen peroxide were found to be promising candidates.[40]

In the approach suggested by Frolov et al.,[40] the fuels are injected directly into the detonation chamber by controlled distributed injection and mixed with each other and air in situ. A more classi-

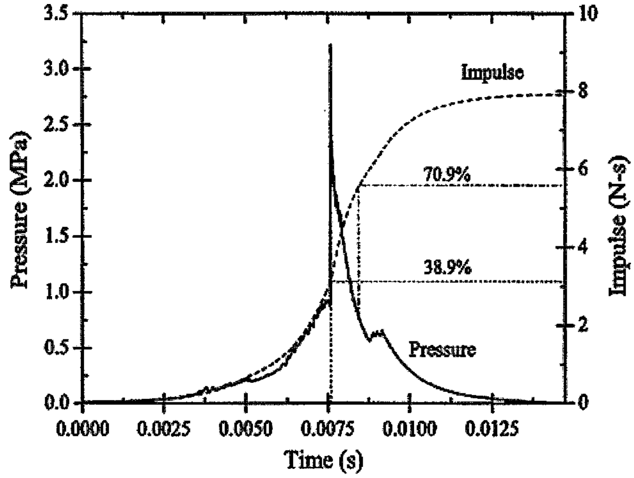


Fig. 5 Pressure and pressure-based impulse after DDT in the same propane–oxygen–nitrogen mixture as for Fig. 3 (from Harris et al.[35]).

cal approach[41] is to initiate detonation in a more easily detonable mixture and then transition it into the mixture of interest. A basic example of this method is the use of a small amount of ethylene–oxygen mixture at the head end of a thrust tube to aid the initiation of detonation in an ethylene–air mixture[42,43] in the same tube. More rapid initiation of a CJ detonation can be achieved by this method than with the Shchelkin spiral in the same tube.[42] A disadvantage of this method for flight applications is the need to carry an additional mixture or have an onboard oxygen generator. Hence, the amount of oxygen needed must be minimized. The volume of the secondary mixture can be reduced by using a smaller tube for the initiator.[41] This initiator is commonly called a predetonator. Diffraction of a detonation from a small tube into an unconfined space or very large tube has been extensively investigated in the past (for example, see Refs. 44–48). Traditionally, the same mixtures are used in both chambers, and the focus is on the survival or failure of the detonation as it diffracts from one geometry into the other. More recently, this problem has been investigated both numerically[49] and experimentally in the context of the pulse detonation engine.[50,51] In two-dimensional simulations[49] of the transmission and transition of detonations from a 40-mm chamber into a 140-mm chamber, it was found that a detonation in a stoichiometric ethylene–air mixture in the small chamber did not survive diffraction, whereas detonation in a stoichiometric ethylene–oxygen mixture did. This was related to the large number of transverse waves in the ethylene–oxygen mixture. Basically, in order to be successful the smaller tube must have sufficient transverse waves (or detonation cells) in order to overcome the effect of the expansion waves from the diffraction corner. Using the ethylene–oxygen mixture in the smaller tube and the ethylene-air mixture in the larger tube, a detonation in the smaller tube was able make the transition in the system simulated. The results from the simulations are in general agreement with the experimental observations from a comparable system.[51] Further efforts are needed to reduce the amount of oxygen required. Brophy et al.[52] suggest that the initiator should be less than 1% by volume to the main chamber.

Desbordes et al.[14] observes that detonation transmission from a small tube to the chamber is easier if combined with additional factors such as local focalization devices, multiple transmission points with focalization, or special designs that ensure a smooth transition. These observations are supported by earlier studies, which indicate that overdriven detonations need reduced critical diameter,[48] that a central circular blockage enhances transmission,[53] and that a diverging cylinder reduces expansion.[54]

Instead of an abrupt area change, the pulsed detonation engine of Baklanov et al.[18] uses a more gradual area change. In their system, illustrated in Fig. 6, detonation is initiated in a 16-mm-diam tube using a spark plug and an electronic ignition system (reported to be similar to that used in automobile engines) and is transmitted into a main chamber through a diverging section. An additional feature of their design is the use of a convergent section at the end of the main chamber in order to obtain a slightly overdriven

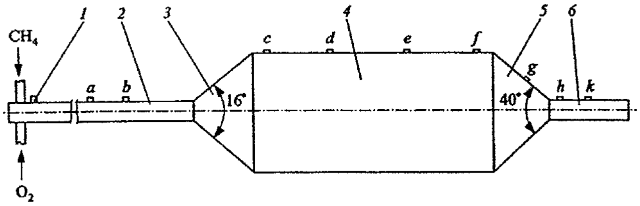


Fig. 6 Variable cross-section pulse detonation tube used by Baklanov et al.[18] The letters a–k refer to locations of pressure gauges and photo diodes. The numbers correlate as follows: 1, spark plug; 2, detonation formation section; 3, expanding cone; 4, main chamber; 5, converging section; and 6, straight tube.

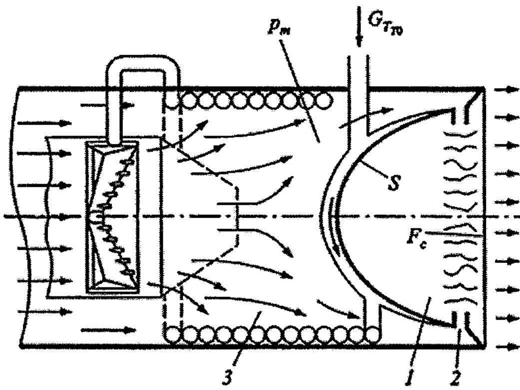


Fig. 7 Schematic of the PDE used by Levin et al.[55]: 1, resonator cavity; 2, annular nozzle; and 3, reactor.

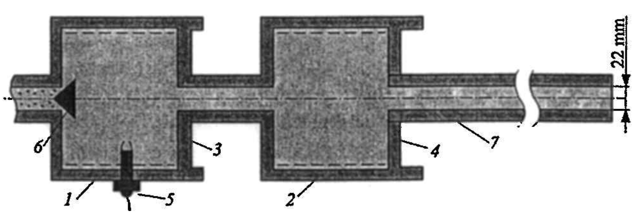


Fig. 8 Schematic of a pulse detonation device with variable geometry turbulizers (from Smirnov et al.[57]).

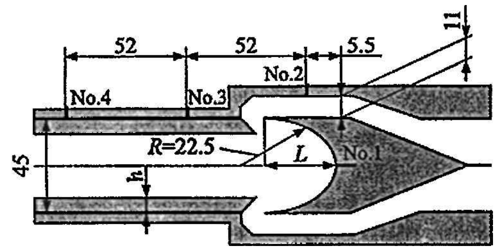


Fig. 9 Simplified sketch of one of the geometries used by Achasov and Penyazkov[59] to enhance DDT with the use of inclined jets and a concave cavity. The dimensions shown are in millimeters.

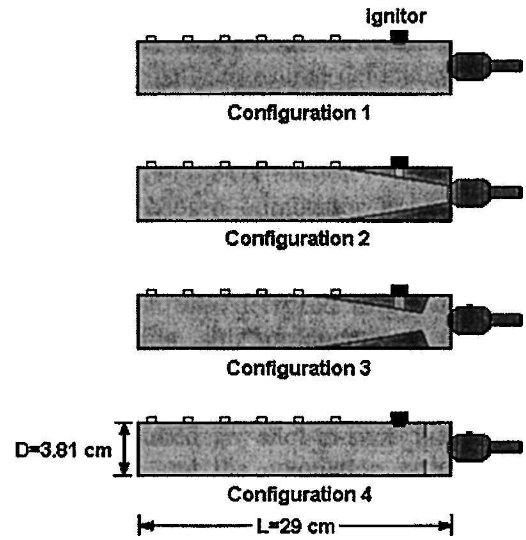


Fig. 10 Schematic of various thrust tube configurations investigated by Brophy and Netzer.[60] The head end of the tube includes a stepped diffuser ramp in configurations 2 and 3, a recirculation cavity in configuration 3, and an orifice plate in configuration 4.

detonation. Because of the presence of this section, they observed a new mode of operation, termed multistep detonation or double nonstationary discontinuity. In this mode flow regimes higher than those in a stationary detonation wave are produced. This behavior occurs because the detonation wave is decoupled in the expanding cone, and then a new detonation occurs in the previously shock-heated mixture. The concentration limits of this mode are narrower than those of the single-step mode.

Another novel approach uses injection of hot radicals in addition to geometric focalization devices to ensure initiation.[55] A schematic of the device is shown in Fig. 7, taken from Levin et al.[55] The combustion process is two-staged. During the first stage, constant pressure combustion of a fuel-rich mixture takes place to generate an oxygen-deficient mixture rich in active radicals. This mixture is injected into the resonator, where additional air is added and detonative combustion takes place. Initiation of the detonation occurs by shock-wave reflections from the resonator wall. A detonation forms at the "focus" and travels through the combustible mixture towards the wall surface.

Smirnov et al.[56,57] have reported on theoretical and experimental investigations of the onset of detonations using one or more turbulizing chambers of wider cross section (see Fig. 8) in a detonation tube to promote the DDT process. They find that using more than two chambers does not help, whereas preheating the gaseous oxidant promotes the onset of detonation. Recent computational studies also suggest that preconditioning the fuel-air mixture using a shock wave can significantly reduce the deflagration to detonation transition distance.[58]

In a comprehensive investigation Achasov and Penyazkov[59] have looked at the use of turbulence-generating grids, shock focusing by reflection from concave surfaces, and the interaction between supersonic jets for promoting detonation initiation. An example is shown in Fig. 9, taken from Achasov and Penyazkov.[59] The mixtures studied were hydrogen–oxygen and acetylene–oxygen mixtures with various amounts of nitrogen, but the results are promising enough for extension to less detonable fuels.

Multiphase Detonations

The work just discussed has primarily focused on gaseous fuels. However, for volume-limited propulsion applications PDEs operating on liquid fuels need to be demonstrated. The problems that must be overcome and the progress to date that has been achieved in the use of liquid JP-10 in pulse detonation engines have been reported in a series of papers by Brophy and Colleagues.[17,52,60–62] Their initial work dealt with characterization of the atomizers used and initiating detonations in JP-10/O2 mixtures.[17] During subsequent work, they evaluated the effects of ignition location, ignition energy and power, and head-end geometry on the repeatability and performance of various configurations (see Fig. 10 from Brophy and Netzer[60]) that were candidates for use as initiators in larger systems with fuel-air mixtures. Configuration 3, which contained a head-end recirculation region and a stepped diffusion ramp, appeared to be the best geometry of those evaluated. The best ignition location for minimum DDT distance was found to be between x/D of 1 to 1.5. Increasing the delivered ignition energy above 500 mJ did not significantly decrease the DDT distance but appeared to increase the repeatability of detonation slightly.

The observation is again made that in a two-phase flow the fuel must be significantly vaporized before a substantial reaction can occur.[63] The fuel was preheated using various inlet temperatures. Corresponding to each temperature, the particle size and amount of

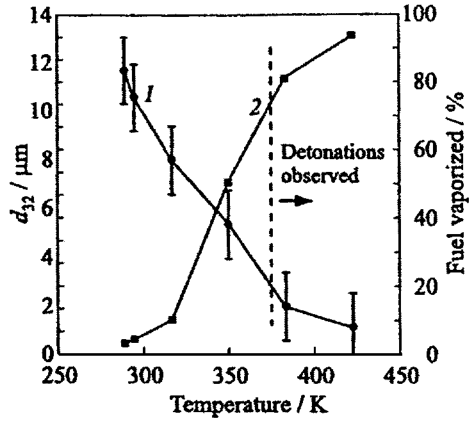


Fig. 11 Sauter mean diameter (1) and percent of fuel vaporized (2) shown as functions of PDE inlet temperatures. The JP-10/air mixtures in which detonations were observed are also indicated (from Brophy and Netzer[60]).

vapor was estimated, as illustrated in Fig. 11 from Brophy et al.[52] Correlating this information with observations of actual detonations showed that JP-10/air detonations occurred only for droplet SMD values of about 3 μ and for an estimated fuel-vapor content of about 70%. The inlet temperature corresponding to these conditions is 375 K. For 425 K the fuel will be completely vaporized. The droplet size also agrees quite well with a simple analysis that gave a value of about 5 μ if the droplet needed to be completely vaporized within 10 mm of the detonation wave.[64] The need to have the droplets vaporize and release their energy close enough to the shock front in order to couple with the front and initiate a detonation has been also highlighted recently in numerical simulations.[65]

The chemistry of JP-10 has also been investigated recently.[22,66] JP-10 is a single-component hydrocarbon, tricyclodecane $C_{10}H_{16}$. It was observed that JP-10 is too large a molecule for a complete detailed description to be currently feasible.[22] Overall approximations were needed, and their analysis yielded a "detailed starting" mechanism consisting of 174 steps involving 36 species. From this starting mechanism they derived mechanisms with various levels of reduction and an ignition time expression that could be directly used in some numerical models. Good agreement (within a factor of two) with experimental data on induction times was also noted. Another observation from the studies of Li et al.[66] is that JP-10 ignition differs qualitatively from ignition of the simpler fuels in that there is an initial endothermic period during which the temperature decreases significantly. Although some dip in temperature is observed for heavy fuels such as heptane, the behavior is stronger here. This suggests the use of JP-10 as an endothermic fuel, that is, as a fuel with increased effectiveness as a coolant. Using it as a coolant will not only help improve the heat management in PDEs but might also be sufficient to help prevaporize some of the fuel and hence aid in the initiation of the detonation in fuel–air mixtures.

Detailed Diagnostics of Detonating Flows

Detailed observations of combustion phenomena during the DDT process have been obtained using OH PLIF and schlieren imaging.[32] In other developments multiplexed diode-laser absorption sensors have been applied for characterizing both reactants and products in pulse detonation flows.[16,31,42,43] The flow sensors monitor oxygen concentration, fuel vapor concentration, fuel droplet size and volume fraction, H_2O concentration, gas temperature gas velocity, soot temperature, and soot volume fraction. The sensors have been demonstrated in PDEs operating on liquid JP-10 and gaseous C_2H_4 fuels. Such detailed diagnostics are invaluable both for providing a detailed characterization of the flowfield and for validating numerical simulations. Typical measurements of this nature are compared later with results of numerical simulations.

Numerical Simulations

Numerical simulations also provide a means of obtaining detailed nonintrusive diagnostics of the flowfield. In general, the accuracy of

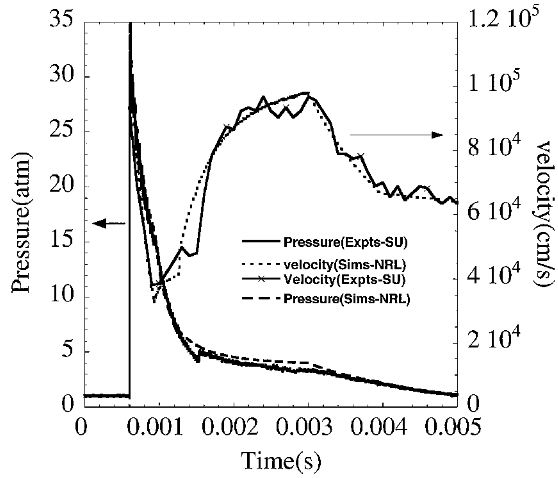


Fig. 12 Comparisons of predicted detonated gas velocities and pressures from Naval Research Laboratory (NRL) simulations to measured velocities and pressures from experiments at Stanford University (from Sanders et al.[43] and Kailasanath[77]).

these results depends on a number of factors such as the fidelity of the physical and chemical models on which the equations are based, the accuracy of the solution algorithm, the numerical resolution used, and the initial and boundary conditions. Models of varying complexity have been employed in the past, and they are discussed in a status report.[67] More recent numerical approaches can be found in Refs. 68–76. Although none of the models adopted have attempted to represent the unsteady, multiphase, reactive, three-dimensional flows in an engine, many of them appear to capture some aspect of the essential physics of the problem in a one-dimensional or two-dimensional geometry. The algorithms used to solve the equations have been predominantly based on nonlinear monotone schemes, which are ideal for such shock-induced flows. Issues related to the validation and verification of PDE computations have been discussed in detail, recently.[77] The adequacy of the models employed to capture the essential physics of the problems investigated can be determined only by direct comparison with experimental data. Such data on flows in pulse detonation engines are currently becoming available, and comparisons are beginning to be made.[42,43,78]

Preliminary experimental data[43] of the time variation of the pressure and fluid velocity at 0.9 L from the head end of a 1604-mm (L)-long tube filled initially with a stoichiometric ethylene–oxygen mixture are shown in Fig. 12, along with the computed values. The peak values as well as the variations in the overall shape of the pressure and velocity are captured very well by this one-dimensional numerical simulation. Preliminary comparisons of the temperature are also encouraging with the maximum differences of about 10%. With the confidence gained by such detailed comparisons, numerical simulations are being used to estimate the system performance[5,71] and investigate means of enhancing performance.[70,79]

Performance Estimates

Performance estimates of pulse detonation engines is another topic that has received significant attention recently.[5,80–91] Before discussing system-level multicycle performance estimates, let us first look at the progress in determining the single-cycle performance of idealized or laboratory pulse detonation engines.

Idealized PDE: Thrust Tube

An idealized PDE is a straight tube without inlets or nozzles, that is, essentially the detonation or thrust tube of a more complex device. Consider the head-end pressure history illustrated in Fig. 13 in order to identify key factors that control the performance of such an idealized device.[92] The abscissa is normalized using the detonation transit time (tube length/CJ detonation velocity), and the ordinate is normalized using the CJ detonation pressure. In Fig. 13 the time history is divided into three distinct stages or regimes: initiation, plateau, and relaxation. Different factors control the different stages. The first stage is dominated by the method used to initiate

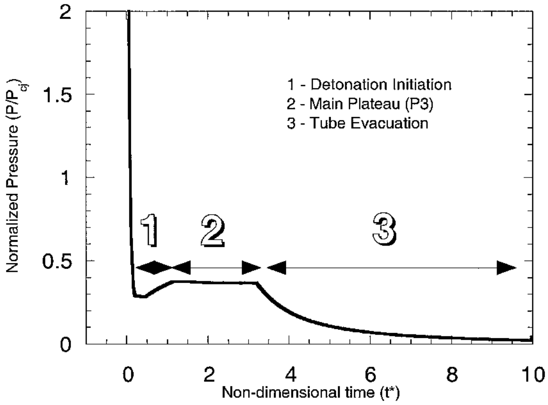


Fig. 13 Different stages in the time evolution of the pressure at the closed end of an idealized PDE thrust tube during a single-cycle operation.

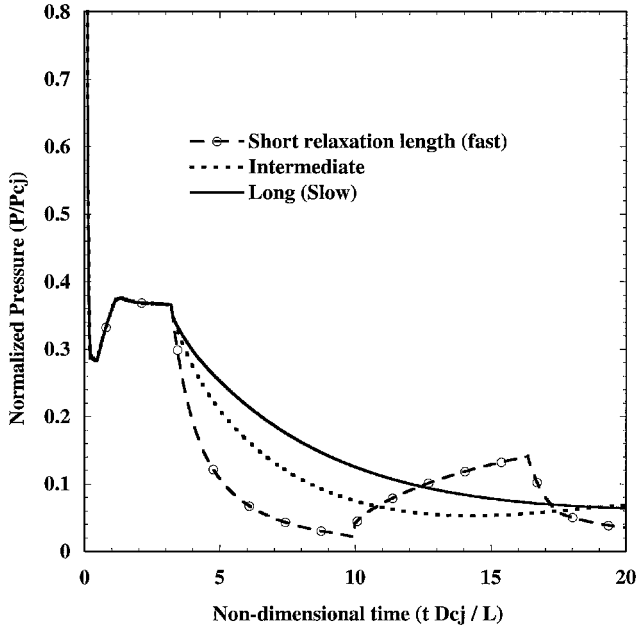


Fig. 14 Effect of different open boundary conditions on pressure evolution at the head end of an idealized PDE thrust tube (adapted from Kailasanath and Patnaik[71]).

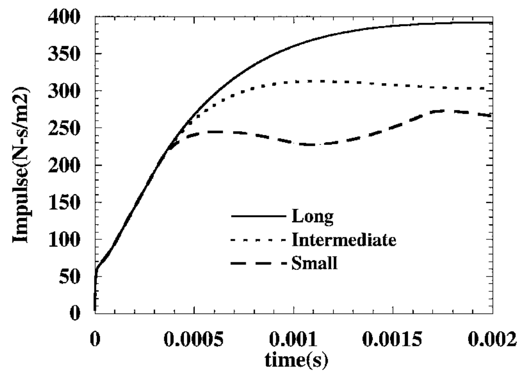


Fig. 15 Impulse corresponding to the different open boundary conditions.

the detonations and to some extent the details of the transition process. Attention is usually focused on the second, the plateau region or stage, and the value of the plateau pressure can be related to the CJ detonation pressure. The third stage describes the relaxation of the plateau pressure towards the ambient value. Although attention is focused here on a single-shot operation, it must be remembered that during multicycle operation of a single tube additional time is needed to refill the thrust tube. In addition, some buffer gas is usually needed between consecutive fillings to avoid premature ignition. These additional processes will significantly add to the overall cycle time and reduce the frequency of operation and hence the thrust. One way to minimize this problem is to have multiple tubes, where some tubes are being filled while the mixtures in other tubes are being detonated or evacuated.[93]

Extensive computational studies of this idealized PDE have been carried out in the past.[67] However, even for the tube filled with a stoichiometric hydrogen-air mixture there was a remarkable variation in the computed performance ranging from 3000 to 8000 s. Recently, detailed numerical simulations[71] have shown that most of this variation could be explained on the basis of the initial and boundary conditions used in the various computational studies.

The explanation provided deals with the specific choice of the numerical boundary conditions used at the exit plane in one-dimensional simulations of the PDE. Several choices for this boundary condition have been tried, and their effect on the flowfield and performance evaluated.[67,71] For example, consider a boundary condition implementation based on the method of characteristics. This ensures that no constraints are imposed on the flow quantities when the outflow is supersonic and enforces the required constraints when the flow becomes subsonic. Even in this formulation,[94] there is a free parameter for the subsonic case that must be specified. Various choices for the free parameter result in different rates of relaxation of the pressure at the open boundary as shown in Fig. 14. The pressure is normalized by the CJ detonation pressure, and the time is normalized by the detonation transit time t^* $(=L/D_{cj})$. The time evolution of the pressures for the three cases is identical until about 3.25 t^* because the detonation initiation parameters and mixture conditions are identical for the three cases and begin to differ only when the expansion waves from the open end of the tube reach the head end. The strength of the expansion waves differs because of differences in the relaxation process at the open end of the tube. For the slow relaxation process (which has an effectively long relaxation length) the pressure reaches the 1 atm mark only by about 20 t^*, whereas for the fast relaxation process (or short relaxation length) it reaches the 1 atm mark by about 6.2 t^*. The areas bounded by the pressure history curves and the abscissa is a measure of the thrust. The thrust is larger for the slower relaxation process but the maximum possible operating frequency would be lower because of the longer time needed to attain this thrust.

The impulse values, for the three cases illustrated in Fig. 15, are identical until the effects of the relaxation process at the open end are felt at the head end. Then, the impulse histories are very different, attaining a maximum value of about 390 N-s/m^2 for the long relaxation length at about 2 ms. This peak value is 60% larger than for the short relaxation length condition and translates into a similar increase in the fuel-based I_{sp}. These results clearly indicate that the pressure relaxation process at the exhaust end of the PDE tube is an important factor in determining the performance. In practice, different relaxation rates can be attained by suitably tailoring the nozzle shape, as will be discussed later.

Effects of Detonation Initiation

In addition to the boundary conditions, the parameters used to initiate the detonations in numerical simulations could also affect the performance estimates. Typically in numerical simulations a small region of high temperature and pressure is used to initiate the detonations. The impact of using such initiators has been discussed before.[71,81] In a series of simulations of the idealized PDE but with exhaust nozzles of different shapes, the contribution from the initiation process was estimated to range from 17 to 27% of the peak impulse.[81] A similar study conducted for a system without any exhaust nozzles (and hence the same pressure relaxation rates) showed that indeed a significant portion of the calculated impulse could be attributed to the initiator used.[71] The initiators used for these simulations are by no means optimal, and some improvement can be obtained by using lower-energy initiators.

An approach to reduce the effect of the initiators used is to consider longer systems with the same initiators. If a detonation can be

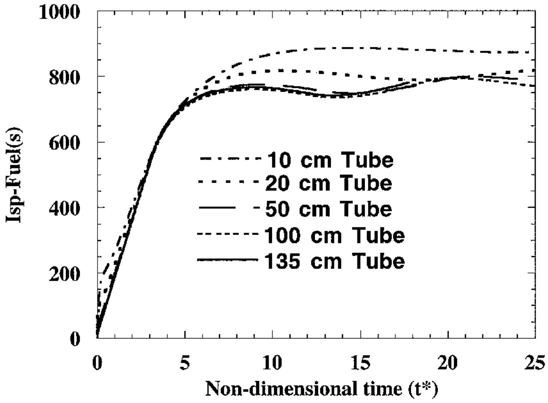


Fig. 16 Effect of tube length and initiator used in numerical simulations on the calculated I_{sp} for an ethylene–oxygen mixture.

initiated in a short tube, the same initiator will be able to initiate the detonation in a longer tube and the relative contribution from the initiator will be reduced. A series of such simulations have been carried out with a stoichiometric ethylene–oxygen mixture initially at 298 K and 1 atm as the detonable mixture. The strength of the initiator needed is also reduced by using this more easily detonable mixture. Tubes of various lengths ranging from 100 to 1350 mm were used in the simulations. In all cases the initiator was a small 5-mm region of high pressure (30 atm) and high temperature (1500 K). The values of the fuel-based specific impulse from this series of simulations are shown in Fig. 16. As before, the abscissa has been made nondimensional using the detonation transit time. When longer and longer systems are considered, the values of the specific impulse eventually become independent of the tube length and essentially independent of the initiator used. This is a way to obtain computationally a clear estimate of the propulsive performance of this idealized PDE. Calculating the values of the mixture-based specific impulse corresponding to the various cases illustrated in Fig. 16 yields values ranging from 165 s for the 1350-mm-long system to about 200 s for the very short 100-mm-long system. Indeed some experiments for comparable systems have provided impulse estimates that are close to the high value.[82,95] The 1350-mm-long tube was chosen to mimic a particular experimental arrangement,[31] and, as will be shown later, measurements from that facility do indicate the lower value very close to the estimate from the simulations. These results highlight that it is not only in simulations that one needs to be very concerned about the initiator used and the effect of geometrical parameters of the system.

Comparison of Performance Estimates

The thrust from the idealized PDE can be obtained either by using a thrust balance or by integrating the pressure history at the head end of the tube. Using the pressure history provides a direct means of comparing the experimental data to the results of numerical predictions. Thrust balance measurements provide an additional check on the calculated thrust or impulse. The equivalence of the two methods has been shown experimentally by Cooper et al.[34] Their study also showed that, when DDT enhancement devices such as obstacles were used, the head-end pressure was no longer a reliable measure of the performance, and direct measurements were needed.

When performing direct comparisons between the predictions of numerical simulations and experimental measurements, the effect of factors such as the initiators used and the boundary conditions at the open end of the tube must be considered. The difficulties of isolating the effects of detonation initiators or transition devices can be reduced by focusing on easily detonable mixtures such as acetylene–oxygen or ethylene–oxygen. The ambiguity about specifying the open boundary conditions can be removed by conducting multidimensional simulations in which the exit plane of the thrust tube is an interior point. These simulations are expensive because regions outside the tube (such as a dump tank) also need to be included in the computational domain. In addition to providing information for direct comparison with experimental data, the results from these

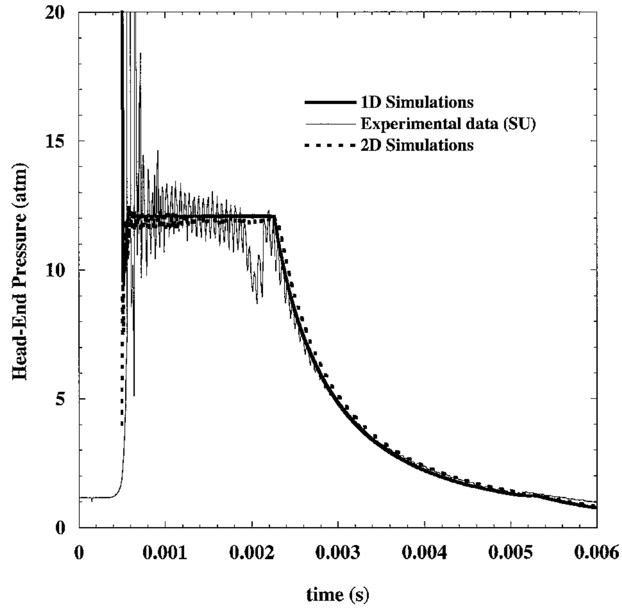


Fig. 17 Comparison of measured and calculated head-end pressure histories in an ethylene–oxygen mixture detonating in a PDE thrust tube (adapted from Sanders et al.[43] and Li and Kailasanath[79]).

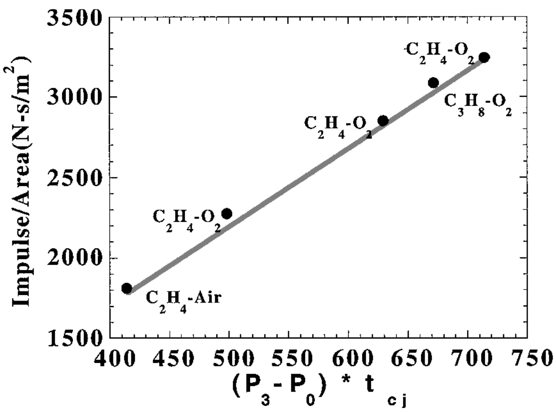


Fig. 18 Generalized impulse from a series of numerical simulations of an idealized PDE thrust tube operating on a variety of fuel–oxygen and fuel–air mixtures.

simulations can be used to determine better approximations for open boundary conditions for use in one-dimensional simulations. Such two-dimensional and one-dimensional simulations have been carried out by Li et al.[70] and Kailasanath and Patnaik,[71] and their results are compared to the measured head-end pressure history from the experiments of Jenkins et al.[78] for a stoichiometric C_2H_4–O_2 mixture in Fig. 17. The very good agreement obtained between predicted and measured pressure histories also results in very good agreement in the values for the impulse and specific impulse estimated from the pressure histories. The values for the impulse calculated from the pressure history for the 1350-mm-long tube were 2807 and 2820 N-s/m^2 for the two- and one-dimensional simulations, respectively. These values correspond to 2079–2089 N-s/m^3 for the impulse per unit volume and are in excellent agreement with the estimates of roughly 2100 N-s/m^3 from a different set of experiments from Cooper et al.[34]

In summary, good estimates of the propulsive performance measures of a stoichiometric ethylene–oxygen mixture initially at 1 atm are as follows: roughly 2100 N-s/m^3 for the impulse (independent of length), roughly 163–168 s for the mixture-based I_{sp}, and 725–745 s for the fuel-based I_{sp}. Similar computations have been carried out for other mixtures and the results generalized, as illustrated in Fig. 18. Here, the impulse from the various cases has been normalized using the predicted overpressure ($P_3 - P_{amb}$) and the residence time of the detonation t_{cj} (length of the detonation tube/CJ detonation velocity of the mixture). What this generalization implies is that the impulse from an idealized PDE can be estimated knowing the plateau pressure P_3 and the detonation velocity. That is, the impulse per unit area is given by

$$I/A = 4.85(P_3 - P_{\mathrm{amb}})t_{\mathrm{cj}} \tag{1}$$

This expression derived from numerical simulations is also similar to the expressions for I_{sp} obtained recently from theoretical analysis by Wintenberger et al.[96] and from experiments by Zitoun and Desbordes[82] and Falempin et al.[97] The results from some recent two-dimensional numerical simulations by Kawai and Fujiwara[20] with hydrogen as the fuel are also in agreement with the preceding expression.

Theoretical Estimates for the Propulsive Performance

A key feature of the propulsive performance of the idealized PDE is the "plateau" region in the pressure history. The early theoretical estimates by Nicholls et al.[98] essentially considered only the plateau region and arrived at what can be considered a lower limit for the estimate. As just discussed, the relaxation of this pressure to the ambient conditions provides additional thrust that cannot be ignored. However, this additional thrust depends on the details of the flowfield and is difficult to estimate accurately from theoretical considerations alone.

The schematic diagram of the pressure history used by Zitoun and Desbordes[82] is depicted in Fig. 19. In this figure p_k corresponds to the plateau pressure p_3, and p_0 refers to the ambient pressure. The effective time t_w is taken to be longer than the duration of the plateau pressure to account for the additional area under the relaxation portion of the pressure history. Normalizing the overpressure $p_k - p_0$ and integrating with the normalized time $t = t/t_{\mathrm{cj}}$, a nondimensional impulse can be calculated. The unknown in the final relation is the effective time t_w, which is taken as

$$t_w = K t_{\mathrm{cj}} \tag{2}$$

where K is a constant to be determined by matching with experimental data. Most recently,[97] a value of about five has been chosen in order to obtain good agreement with experimental data.[14] Assuming that this constant is only dependent on the device and not on any of the mixture properties or initial conditions, the values of the specific impulse for other mixtures can be estimated from the empirical formula:

$$I_{\mathrm{sp}} = \frac{5(p_k - p_0)}{g\rho_0 D_{\mathrm{cj}}} \tag{3}$$

In a variation of the preceding approach, the effective time t_w has been divided into three segments by Wintenberger et al.,[96] as shown in Fig. 20. The first segment t_1 is just equal to t_{cj}. The other two time segments are defined as

$$t_2 = \alpha L/a_3 \qquad \text{and} \qquad t_3 = \beta L/a_3 \tag{4}$$

where a_3 is the sound speed corresponding to the conditions at the end of the Taylor wave. The constant α has been estimated using a single γ ideal detonation model, whereas β is determined from experimental data, leading to the following expression for the impulse per unit volume:

$$\frac{I}{V} = \frac{4.3(p_3 - p_0)}{D_{\mathrm{cj}}} \tag{5}$$

where the pressures are in pascals and the detonation velocity D_{cj} is in meters per second.

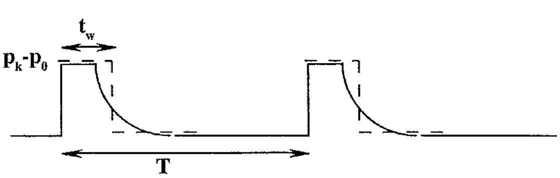


Fig. 19 Schematic showing a typical pressure trace and various factors used in a model to estimate the performance of an idealized PDE (from Desbordes et al.[14]).

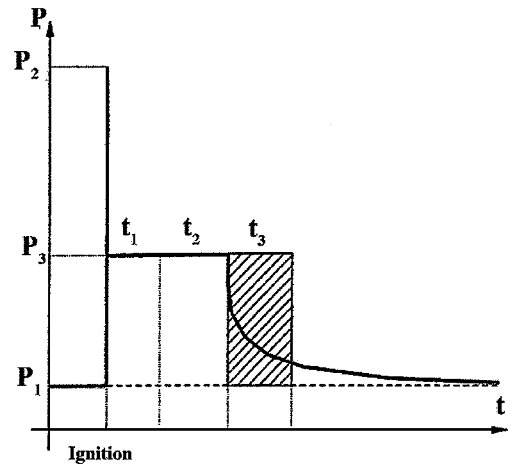


Fig. 20 Idealized pressure trace and parameters used in the analytical model of Wintenberger et al.[96]

Whether they are derived completely from numerical simulations or based partly on experimental data for the pressure relaxation, the three general expressions [Eqs. (1), (3), and (5)] provide equivalent measures for the idealized PDE performance. They differ only in the constant of proportionality. The expression in Eq. (5) appears to give a lower value primarily because the experimental measurements used to calibrate the model include some losses caused by transition devices used to enhance detonation initiation. Considering this difference, all three expressions provide fairly good first estimates of the single-cycle performance of the idealized PDE. The utility of such expressions has been highlighted by the work of Wintenberger et al.,[96] where their expression is used to explore the influence of various parameters such as initial temperature, initial pressure, and equivalence ratio on performance.

There are also other theoretical estimates for the propulsive performance of the idealized PDE.[84–86] In one approach[86] analysis originally developed for wave rotors is extended to the PDE. In other studies[84,85] the PDE cycle is approximated by a constant volume process, and purely analytical performance measures have been calculated. One of these studies[85] estimates the mixture-based specific impulse for a typical hydrocarbon fuel to vary between about 170 to 210 s as the Mach number varies from 0 to 2. If direct comparisons of these estimates with experimental data are promising, these can provide a means of estimating a limiting performance value from purely analytical considerations.

Performance analysis based on zero-dimensional thermodynamic cycle analysis of the detonation process has also been carried out by a number of investigators (e.g., Refs. 1, 4, 52, 55, and 91). All of these studies have confirmed the thermodynamic efficiency of the detonation process, compared to a classical constant pressure heat-addition process over a wide range of parameters. The advantage of the detonation process is especially large for static conditions and decreases as the velocity (or static temperature ratio) increases. However, it has been difficult to relate these superior thermodynamic efficiencies directly to improved propulsive performance. When losses are considered, one study[91] finds that the PDE performance suffers more than an engine based on the constant pressure cycle and falls slightly below that of the constant pressure cycle engine for even moderate static temperature ratios. Another recent study also finds that the advantages claimed over the constant pressure cycle engine mostly disappear when the effects of dissociation and forward flight are considered.[88,89] These results are intriguing, and further studies are needed to validate these observations with experimental data and more detailed analysis such as numerical simulations.

Methods to Enhance the Propulsive Performance

The key to enhancing the performance of the idealized PDE would be to alter the time history of the head-end pressure. As already discussed, altering the pressure relaxation rates would alter the performance, and nozzles might be a practical way in which to alter the pressure relaxation rates. Another approach that has been investigated by several investigators (e.g., Refs. 21, 42, 70, 79–81, and

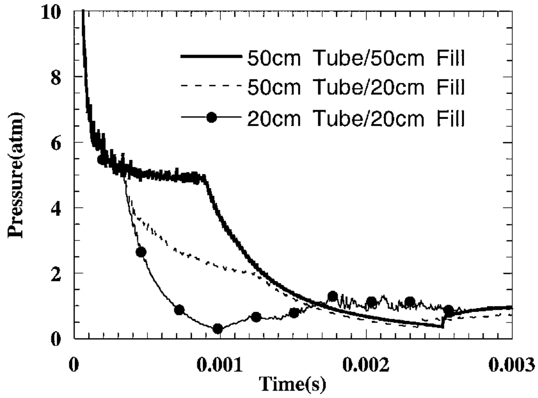


Fig. 21 Comparisons of the head-end pressure histories from three simulations of PDEs of different lengths and different extents of fuel fill (from Li et al.[70]).

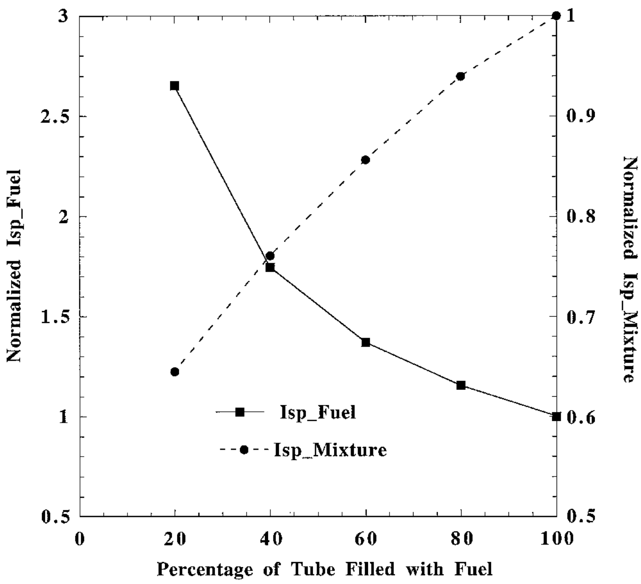


Fig. 22 Effect of percentage of fuel fill on mixture and fuel-based specific impulses from simulations of a PDE thrust tube filled with an ethylene–air mixture (adapted from Li et al.[70]).

99–102) is to partially fill the thrust tube with a detonable mixture and fill the rest of the tube with air. The operational benefits of this approach in airbreathing propulsion include a means of varying the thrust other than by varying the frequency of operation.

The results from three numerical simulations by Li et al.[70] are shown in Fig. 21 to illustrate the advantages of partial-fuel fill. In two of these simulations, a 50-cm-long tube is filled completely or partially up to 20 cm with an ethylene–air mixture. In the third simulation a 20-cm-long tube was completely filled with the same fuel–air mixture. The time histories clearly show two different trends in the pressure history for the partially filled case. Initially it follows the 20-cm fully filled case, but then turns toward the fully filled 50-cm case. Detailed analysis of such simulations, discussed by Li et al.[70] and Li and Kailasanath,[79] shows that the reason for this result is a result of the presence of two different sets of expansion waves, one from the fuel–air interface and the other from the exit end of the tube. When these different sets of expansion waves reach the thrust wall, the pressure decays at different rates because the strengths of the expansion waves are different. Equivalently, the extra area enclosed by the pressure curve for the partially filled case can also be viewed as caused by the shock compression of the air in the tube. Calculating the fuel-based specific impulse as usual will provide an enhancement because the amount of fuel in the partially filled case is the same as the fully filled 20-cm case. However, if the mass of the air in the tube is taken into account this enhancement vanishes, and the mixture-based I_{sp} decreases with the decrease in the amount of fuel fill. This is highlighted in Fig. 22, where both the fuel-based and

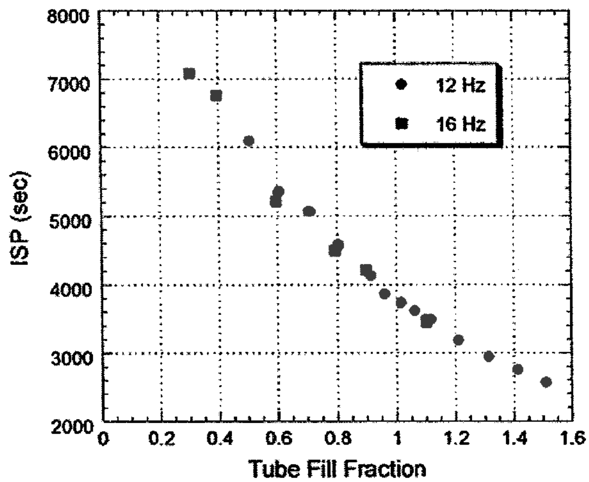


Fig. 23 Effect of partial-fuel fill on the measured specific impulse during multicycle operations of a PDE operating on a hydrogen–air mixture (from Schauer et al.[21]).

mixture-based specific impulses are shown from a series of simulations in which a 50-cm-long tube was filled to various lengths with an ethylene-air mixture.[70] Experiments with various degrees of fuel fill have shown a very similar behavior in the pressure histories[42,78] and fuel-based I_{sp}.[102] More recent experiments[21,101] have also verified the effect during multicycle operation. The effects of the tube-fill fraction on the fuel-based I_{sp} during different multicycle operations of a hydrogen-air PDE are shown in Fig. 23 (from Ref. 21). The fill fractions greater than one in the figure indicate cases where the tube is overfilled with the detonable mixture, presumably forming a free cloud at the tube exit.[21] The observed gain in I_{sp} is seen to be independent of the frequency of operation and is comparable to that obtained during a single cycle. Analytical[99] and numerical investigations[103] have also attempted to derive limiting values for the enhancement that is possible by partially filling the tube. Another method to enhance the performance is with the use of nozzles, as discussed next.

Nozzles for Pulse Detonation Engines

Nozzles for the PDE present challenging design and integration issues because of the inherently unsteady nature of the pulse detonation process. The overall system can be made to appear steady by using a high-frequency, multitube system. But even in this case, designing an efficient common flow path for the exhaust from the individual thrust tubes is an issue that needs to be addressed.

There have been several computational and experimental investigations in the past on the effect of nozzles (e.g., Refs. 80–83, 97, and 104–107), and these have been discussed in detail in an earlier paper.[6] Only the highlights of the observations made in that paper are presented here along with an emphasis on the most recent studies. That review showed several common observations but also revealed some apparently contradictory conclusions.

Daniau et al.[104] experimentally investigated nozzles of different shapes and lengths. They focused on cases where the nozzle serves only as an exhaust for the detonation products. That is, the nozzle section does not have any detonable mixture but is filled with air. Hence the partial fuel-fill effects discussed earlier are to be expected in their results. Both thrust wall pressure measurements as well as direct measurements of the impulse using a ballistic pendulum were used to investigate the various cases. The basic thrust tube used was 50 mm in diameter and 100 mm in length.[104] For a diverging nozzle, also of length 100 mm, nozzles of various angles all produce an increase in I_{sp}. This was attributed to an increase in the area over which the pressure can act. However, the time at which the head-end pressure attains the ambient value (1 atm) is different, in general, for the various nozzles. Hence the maximum possible cycling frequency will be affected if the refilling time is based on a specified value of the pressure at the head end. Interestingly, Daniau et al.[104] also report a specific case where the time when the head-end pressure reaches the atmospheric value is the same as the reference case. Therefore,

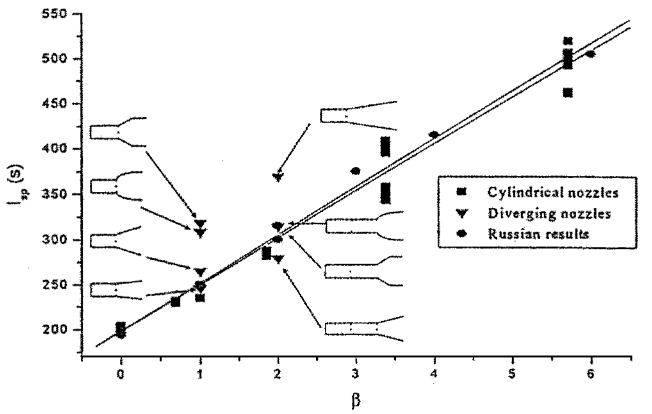


Fig. 24 Impact of nozzles of various lengths and shapes on the measured specific impulse. The parameter β is the ratio of the nozzle length to the detonation chamber length (from Falempin et al.[97]).

it is possible to increase the I_{sp} using a suitably designed nozzle without affecting the maximum cycling frequency.

In general, divergent nozzles yield higher impulse as illustrated in Fig. 24 (taken from Falempin et al.[97]), which summarizes the results from a number of investigations. In this figure β is the ratio of the nozzle length to the combustion chamber length. Although in most cases the higher impulse also occurs later in time and hence could increase the cycle time, several designs are possible to attain the higher performance without significantly affecting the cycle time.[97] Among the diverging nozzles, the bell-shaped nozzle has shown significant improvements in performance in at least three independent studies.[80,81,104] All studies with convergent nozzles show shock reflections that propagate upstream and interfere with the refilling process (e.g., Refs. 80, 106, and 107).

There are also some contradictory observations. For example, Mohanraj and Merkle[83] conclude that a conical divergent nozzle having an expansion ratio 4 is detrimental to performance when the ambient pressure is 1 atm, whereas Daniau et al.[104] find that all of the diverging nozzles they experimented with show an improvement in performance. One of the possible reasons for the difference in the two observations is that in the experiments the nozzle section is filled only with air, whereas in the simulations there is detonable mixture in the nozzle. The increase in impulse caused by the additional detonable mixture might not adequately compensate for the increase in mass and consequent decrement in the I_{sp}. The expansion ratios considered in the two studies are also different. A recent experimental study by Cooper et al.[34] with a diverging conical nozzle having a half-angle of 8 deg and a length of 300 mm attached to a tube of length 1016 mm with internal obstacles to enhance DDT also did not show a significant increase in impulse.

The effects of partially filling the thrust tube with the detonable mixture and filling the rest of the tube with air have also been interpreted as having a straight nozzle.[80–82] There is general agreement among the various studies that straight nozzles result in an increase in the fuel-based I_{sp}. Some studies suggest that this increase in performance will come at the expense of the cycle frequency.

In some previous computational studies[5,67,71] the rate of relaxation of the pressure within the tube to the ambient values was found to be a critical factor determining the performance of a straight tube PDE. Higher specific impulse was attained with a slower relaxation rate. This is consistent with the results discussed here on straight nozzles. The studies with the diverging nozzle suggest an alternate strategy where a faster relaxation rate gives better performance because of the larger effective area on which the thrust can act. Under some circumstances[34] it appears that the increase in effective area might just compensate for the expansion waves from the area change resulting in minimal and no gain. In any case this additional area comes with its own penalty, an increase in the engine cross section and consequently an increase in the drag for a system with a single tube and attached nozzle. Suitable design of a multitube system might be able to overcome this limitation.

Direct comparisons between the various studies have not been possible because of the wide variation of the nozzle parameters (shape, size, ambient pressure, and extent of fuel fill) and the detonable mixtures considered. Another factor that has created some confusion in the interpretation of previous results is that in some of those studies the nozzle is prefilled with a detonable mixture, whereas in others it is filled with the ambient air.

The discussion so far has focused on expansion of the detonation products to a background pressure of 1 atm because that is what is done usually in laboratory experiments. However, for most flight applications expansion to other ambient conditions also needs to be considered. With a primary focus on rocket applications, Mohanraj and Merkle[83] have used quasi-one-dimensional numerical simulations to study the effects of varying the ambient pressure. The total length of the PDE simulated is 500 mm including a 170-mm-long conical nozzle having a divergent cross section. The nozzle expansion ratio is four. They find that the nozzle provides an increase in I_{sp} only at low ambient pressures and is actually detrimental at higher ambient pressures. The higher pressures referred to are values between 0.2 and 1 atm. At first glance this result appears to contradict some of the earlier observations at 1 atm, and the plausible reasons for this difference have already been discussed. For low ambient pressure cases they suggest using a convergent section in the nozzle to retain a higher average pressure in the chamber. This raises issues with heat transfer and cooling, but the potential benefits appear promising. Effects of nozzle area expansion ratio for a conical divergent nozzle at vacuum conditions have also been reported.[83] For these cases a fixed frequency of 500 Hz was used, and the system was partially filled with fuel up to 67% of the length of the chamber, that is, up to the start of the nozzle. Higher I_{sp} was observed as a result of partial fill, as expected. The higher I_{sp} was also accompanied by lower thrust caused by lower mass flow rate. This was found to be true for all expansion ratios considered.

Most previous studies have focused on a multicycle operation using a single tube. Furthermore, the blowdown process is assumed to be a major portion of the overall cycle. If the purging and refilling times are the dominant portion of the overall cycle, small changes in the blowdown phase will not significantly affect the overall system frequency.[90] Practical applications are likely to involve systems with multiple thrust tubes.[108] In these cases the optimization process is quite different because the refilling process is less coupled to the blowdown process. An increase in the blowdown time for each tube might be acceptable for the higher thrust and impulse that will be produced by each tube. However, design of the exhaust nozzle for such multitube systems adds complexity. The interaction among the different tubes and the timing of the various processes are beginning to be investigated.[109] The advantages of a common nozzle are also discussed. A divergent nozzle section for a single tube will act as a diffuser rather than a flow accelerator during large portions of the cycle when the total pressure in the unsteady exhaust stream becomes too low. Multiple tubes discharging into a common nozzle provide higher average total pressures that help to ensure that the nozzle accelerates the flow over a larger fraction of the PDE cycle. The throat of the common nozzle can be chosen to provide an effective backpressure at the exit of the detonation tubes that increases their average operating pressure and enables them to generate more thrust.

Inlets for Pulse Detonation Engines

Appropriate inlets for airbreathing PDEs is a topic that appears to have received little attention, although it is not clear how much of the extensive work done in the past on high-speed inlets will be directly applicable to PDEs. In fact, Butuk et al.[110] state that "one of the key technology areas requiring development is in the integration of the unsteady PDE to the steady vehicle inlet." Pegg et al.[111] addressed two concerns regarding this integration: 1) Will the abrupt closure of valves trigger hammershocks and cause an inlet unstart? 2) Can a stable shock system be established in the inlet of a PDE? They carried out a conceptual design where a single vehicle inlet duct supplies air to multiple PDE modules. In the proposed design a shock trap boundary-layer bleed system was able to stabilize the terminal shock train in the inlet, and there was insufficient time for the formation of potentially destabilizing hammershocks.

Other recent efforts have focused on demonstrating the operation of single and multitube combustors coupled to an inlet using a rotary valve mechanism.[112] The valve serves both to 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. The rotating valve introduces a moving part, with its associated controls and power requirements. Hence, Butuk et al.[110] propose a fluidic valve concept having no moving parts. Results using a numerical code and an analytical model are also presented in their paper.

Mullagiri et al.[113] tested a supersonic inlet with backpressure excitation to simulate the flowfield experienced by the inlet of a PDE at Mach 2.5. The excitation was varied from 15 to 50 Hz, and the amplitude was varied by increasing blockage at the exit plane from 32 to 83%. Flow visualization using schlieren images was used to observe the shock motion, and pressure-sensitive paint was used to obtain the lower wall surface-pressure distribution. They found that pressure oscillations inside the inlet were confined to the region downstream of the throat and that no adverse effects were observed upstream of the throat. Other recent investigations have studied the effect of varying the inlet cross-sectional area on performance of a simple tube PDE and find "a decrease of only 25%" in I_{sp}.[14]

Coleman[7] notes that the low static pressure at high altitudes will influence the total pressure recovery of PDE inlets and therefore influence the detonability characteristics of the propellants. As the initial pressure drops, cell sizes increase, and the mixture becomes less detonable. Airbreathing PDE operation could be altitude limited unless some type of backpressurization can be provided. Optimization of air inlets in subsonic and supersonic flight remains an important issue that needs further study specifically focused on PDEs.

System-Level Performance Estimates

System-level performance estimates are needed in order to be able to compare the estimated performance of PDEs to existing propulsion systems. Such performance estimates are usually obtained from an overall engine performance model. Although off-the-shelf models exist for established propulsion systems, using such models for innovative concepts such as the PDE presents problems because some of the essential physics of such newer systems might not be adequately represented in these models. A solution to this dilemma is to develop performance models specifically for the PDE. An overview of the various components that need to be considered for the PDE and techniques for modeling each component have been discussed previously by Bratkovich and Bussing.[114]

More recently, Wu et al.[90] have developed a global performance model and estimated the performance of a six-tube, airbreathing PDE using hydrogen as the fuel. For an altitude of 9.3 km and freestream Mach number of 2.1, they calculate a specific impulse of 911 s for a PDE operating at 244 Hz. They also find that using a converging or diverging nozzle does not provide any improvement of the impulse compared to a PDE without a nozzle. They suggest the use of a pulsed ejector configuration, in which fluid interactions with an ambient or secondary stream take place, might offer a means to improve performance.

Because PDE technology is still in its infancy, the uncertainty of each component efficiency is greater than for conventional systems. For example, earlier discussion in this paper has highlighted the limited knowledge available concerning appropriate inlets and nozzles for PDEs over a range of operating conditions. Small uncertainties for each component could translate into significant uncertainty for the overall system, and therefore system-level performance projections made to date must be considered very preliminary.

Application Studies

In spite of (or perhaps because of) the major uncertainties at the component level and the significant difficulties that must be overcome to provide reliable multicycle operation with practical fuels, a vast number of applications for the PDE have been proposed over the years. The suggestions during the past two years include "supersonic reconnaissance vehicles, high-speed munitions, miniature cruise missiles, long-range sensor platforms, mother vehicles, and launch vehicles for minisatellites"[115]; as afterburners either in the bypass duct[116] or in the aft[117]; for driving magnetohydrodynamic electric power generators[118]; integration with a wave-rotor device[119]; combined cycle engines[120,121]; low-cost unmanned air vehicles (UAV) and unmanned combat air vehicles (UCAV)[122]; and single-stage-to-orbit (SSTO) launcher,[97] to name a few.

Rocket-engine applications have received considerable attention partly because hydrogen is an acceptable fuel, and inlet operation over a range of flight conditions is no longer an issue. The rocket mode of operation is very similar to the airbreathing engine with ignition at the closed end, except that the oxidizer also needs to be injected into the system periodically. The paper by Bratkovich et al.[123] provides an introduction to this application, whereas a more recent paper from the same group[124] provides a status report on rocket-engine hardware development. They report that a water-cooled six-tube system, with each tube operating at 80 Hz (to give an overall engine frequency of 480 Hz), has been fired for 10 s of continuous operation. They also emphasize the need for elevated operating pressure for good performance under flight conditions. A common nozzle for a multitube system could help maintain the backpressure. Modeling of pulse detonation rocket engines has also been presented by Cambier[68] and Mohanraj and Merkle.[83]

The potential performance gains that can be gained by using PDEs in the bypass duct of a turbofan,[116] and as an afterburner,[117] have been assessed. Issues that need to be resolved include the interaction between the pressure waves and the engine fan, leading to potential fan stall, and the merging of the bypass duct flow with the core flow. Based on wave rotor technology, a new type of nonsteady ejector has been proposed to enhance the performance of pulsed detonation combustors.[119] This concept integrates a pulsed detonation process with an efficient momentum transfer process using specially shaped rotating channels of a single wave-rotor device.

Although most of the emphasis on the PDE has been as a thrust-producing device, recently a hybrid piston-pulse detonation engine was developed to demonstrate that shaft horsepower could be extracted from the device while still producing significant thrust.[125] This is important because if this were not possible, a second engine or device would be required to provide auxiliary power for some applications. In another investigation[126] two methods to self-aspirate a PDE, namely, an ejector pump and a turbocharger, were also successfully demonstrated.

Falempin et al.[122] have considered PDEs for lowcost missiles for UAV and UCAV applications. Here the emphasis is not on high performance but on the simplicity of the device and potential cost savings. In another study they propose a SSTO launcher, which uses the same engine from takeoff to orbit.[97] The potential for PDEs to operate over a wide range of conditions has been exploited by Munipalli et al.[120] A single flow-path, combined-cycle engine was studied with four modes of operation: an ejector augmented pulse detonation rocket engine (PDRE) for takeoff to moderate supersonic Mach numbers; pulsed normal detonation wave mode for $M < M_{cj}$; an oblique detonation mode for $M > M_{cj}$; and a pure PDRE for high-altitude flight (Fig. 25). More details on the pulsed normal detonation wave engine mode have been given by Wilson et al.[121] They consider a supersonic flow in the combustor with normal detonation waves propagating upstream. This approach eliminates the need to reduce the inlet flow velocity to subsonic speeds prior to entering the combustion chamber and also allows the detonation chamber temperature to be kept below the autoignition temperature of the fuel-air mixture. Preliminary performance estimates suggest that thrust and specific impulse are comparable or superior to existing rocket-based combined-cycle engine concepts.

A direct comparison of the measured performance of a simple device operated as a PDE and a ramjet has been reported.[115] The system illustrated in Fig. 26 is approximately 10 in. (254 mm) long with an i.d. of 1.875 in. (47.63 mm). A conical nozzle with exit area of 0.44 in.^{2} (28.39 mm^2) was used, and the effective flow area of the blockage element upstream was 0.75 in.^{2} (48.39 mm^2). The airflow rate was 0.1 lb/s (45.36 g/s), corresponding to a Mach 0.7 flight condition. Hydrogen–air at a ϕ of 0.6 was the detonable mixture. An

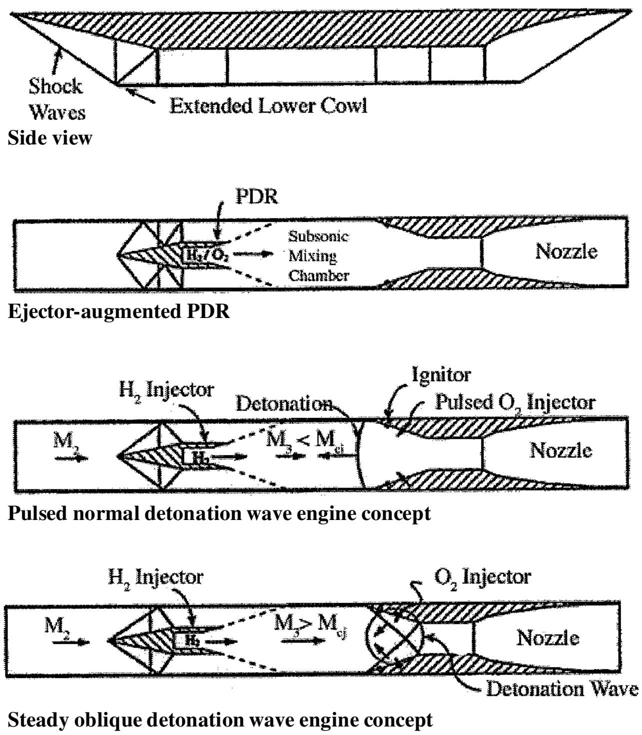


Fig. 25 Proposed multimode propulsion concept of Munipalli et al.[120]

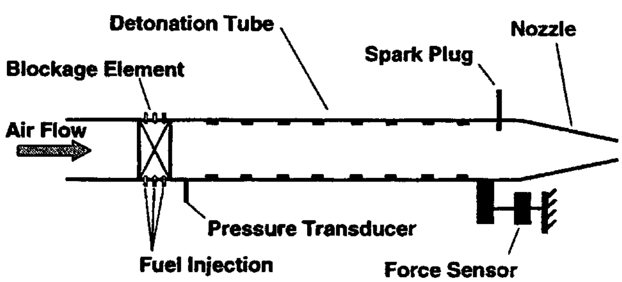


Fig. 26 Schematic of the pulsed detonation engine apparatus used in the experiments of McManus et al.[115]

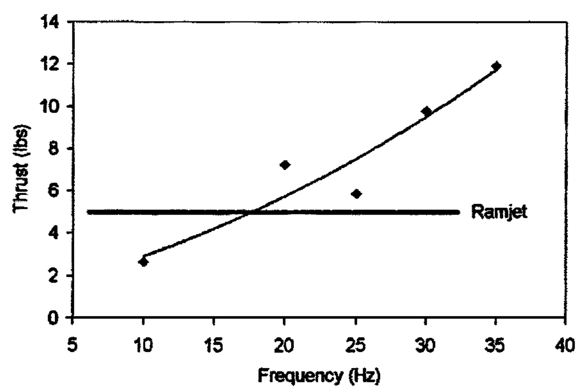


Fig. 27 Comparison of the average thrust from the device shown in Fig. 26, operated as a PDE and a ramjet (from McManus et al.[115]).

interesting feature of this device is the spark-plug location for ignition, downstream near the nozzle entrance. Thrust levels increased from 2.5 lb (11.12 N) at 10 Hz to 12 lb (53.38) at 35 Hz (Fig. 27, from McManus et al.[115]). They also ran the system as a ramjet and obtained 5 lb (22.24 N) of thrust and even this required nearly twice the fuel flow rate. When operated at similar thrust levels, thrust specific fuel consumption (TSFC) of the PDE was 0.40 lb/h/lb (11.33 kg/s/N) compared to 0.67 lb/h/lb (18.98 kg/s/N) for the ramjet. The PDE exhibited even better efficiency at higher thrust levels with TSFC of 0.17 lb/h/lb (4.82 kg/s/N) at an operating frequency of 35 Hz and an average thrust output of 12 lb (53.38 N). Although these are far from flight-ready hardware, this appears to be the first system that has clearly shown better performance for the PDE than a conventional propulsion system.

Kaemming[127] provides an integrated vehicle comparison of a turboramjet engine and a PDE for a Mach 3.5 flight at 80,000 ft (24,384 m). For both conceptual vehicles they consider "first level weights, structural layout, aerodynamics, stability and control, and installed propulsion system performance estimates." They find that the turboramjet engine possesses a much higher thrust at low speeds because of the ability to develop high engine pressure ratios at low speeds. PDE has very low thrust at low speeds because it depends on inlet ram to establish the pressure ratio. However, the PDE thrust increases with speed faster than the turboramjet. Overall, they observe higher thrust density (thrust per unit area) for the turboramjet than the PDE 1) because of the cyclic nature of PDE and 2) because the turbine engine can be designed for a wider range of pressure ratios. Hence the PDE must accommodate a larger engine cross-sectional area. However, they note that the integration flexibility of the PDE allows a better tailoring of the overall vehicle area distribution to minimize supersonic drag. Another advantage they find for the PDE is better fuel efficiency at high supersonic speeds. If these advantages are utilized, they observe an 11 to 21% takeoff gross weight benefit for the PDE, depending on the mission profile. Of course, such performance advantages are conditioned by the current state of knowledge about the PDE. They conclude that, "PDE can show vehicle level performance advantages over conventional turbine based engines. However, performance advantages are only realized when the vehicle is designed to capitalize on the strengths of the PDE with accommodation for its weaknesses."[127]

Conclusions

Significant progress is noted in the research toward the development of pulse detonation engines for airbreathing and rocket applications. The development of advanced laser-based diagnostics has played a key role in the validation of numerical models. Several independent investigations (both experimental and numerical) are used to arrive at a converged value for the performance of an idealized PDE operating on an ethylene–oxygen mixture. Simple theoretical expressions, calibrated with experimental data or from numerical simulations, are now available for quick performance estimates. The enhancement of fuel-based specific impulse values caused by partial-fuel fill effects has been demonstrated by several experimental and numerical studies. Several innovative approaches have been developed to initiate detonations in hydrocarbon fuel–air mixtures. Atomizers for generating very fine droplets and for successful detonations with heated JP-10/air mixtures have been reported.

Inlets and nozzles for pulse detonation engines are still in the early stages of development. As a result, there are still significant uncertainties in overall system-level performance estimates. A wide variety of applications for the PDE have been proposed, but the analyses are still preliminary because of the system-level uncertainties. Specific applications and system-level developments that can take advantage of the pulse detonation process, while overcoming some of its limitations, are needed. It is hoped that this review provides a clearer picture of our current understanding and highlights the need for additional research on PDEs.

Acknowledgments

This work was sponsored by the U.S. Office of Naval Research through the Mechanics and Energy Conversion Division and the Naval Research Laboratory.

References

[1]Kailasanath, K., "Review of Propulsion Applications of Detonation Waves," *AIAA Journal*, Vol. 38, No. 9, 2000, pp. 1698–1708.

[2]Eidelman, S., Grossmann, W., and Lottati, I., "Review of Propulsion Applications and Numerical Simulations of the Pulse Detonation Engine Concept," *Journal of Propulsion and Power*, Vol. 7, No. 6, 1991, pp. 857–865.

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

[4]Bussing, T., and Pappas, G., "Pulse Detonation Engine Theory and Concepts," *Developments in High-Speed-Vehicle Propulsion Systems*, edited by S. N. B. Murthy and E. T. Curran, Vol. 165, Progress in Astronautics and Aeronautics, AIAA, Reston, VA, 1996, pp. 421–472.

[5]Kailasanath, K., "A Review of PDE Research—Performance Estimates," AIAA Paper 2001-0474, Jan. 2001.

[6]Kailasanath, K., "A Review of Research on Pulse Detonation Engine Nozzles," AIAA Paper 2001-3932, July 2001.

[7]Coleman, M. L., "Pulse Detonation Propulsion Systems," *Proceedings of the 50th JANNAF Propulsion Meeting*, JPM CD-01, CPIA Publication 705, Columbia, MD, July 2001.

[8]Roy, G. D., "Practical Pulse Detonation Engines—How Far Are They?," International Symposium on Airbreathing Engines, Paper 2001-1170, Sept. 2001.

[9]Hayashi, A. K., and Fujiwara, T., "Recent Progress of Japanese PDE Research," AIAA Paper 2002-0475, Jan. 2002.

[10]*Proceedings of the Fifteenth ONR Propulsion Meeting*, edited by G. D. Roy and A. Gupta, Office of Naval Research, Arlington, VA, 2002, pp. 155–257.

[11]*Proceedings of the 18th International Colloquium on the Dynamics of Explosions and Reactive Systems* [CD-ROM], Univ. of Washington, Seattle, WA, July 2001.

[12]Roy, G. D., Frolov, S. M., Netzer, D. W., and Borisov, A. A., (eds.), *High-Speed Deflagration and Detonation: Fundamentals and Control*, ELEX-KM Publishers, Moscow, 2001.

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

[14]Desbordes, D., Daniau, E., and Zitoun, R., "Pulsed Detonation Propulsion: Key Issues," *High-Speed Deflagration and Detonation: Fundamentals and Control*, edited by G. D. Roy, S. M. Frolov, D. W. Netzer, and A. A. Borisov, ELEX-KM Publishers, Moscow, 2001, pp. 177–192.

[15]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.

[16]Jenkins, J. P., Sanders, S. T., Baldwin, J. A., Fan, W., Baer, D. S., and Hanson, R. K., "Diode-Laser Based Sensors for Pulsed Detonation Engine Flows," *High-Speed Deflagration and Detonation: Fundamentals and Control*, edited by G. D. Roy, S. M. Frolov, D. W. Netzer, and A. A. Borisov, ELEX-KM Publishers, Moscow, 2001, pp. 273–288.

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

[18]Baklanov, D. I., Gvozdeva, L. G., and Scherbak, N. B., "Pulsed Detonation Combustion Chamber for PDE," *High-Speed Deflagration and Detonation: Fundamentals and Control*, edited by G. D. Roy, S. M. Frolov, D. W. Netzer, and A. A. Borisov, ELEX-KM Publishers, Moscow, 2001, pp. 239–250.

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

[20]Kawai, S., and Fujiwara, T., "Numerical Analysis of 1st and 2nd Cycles of Oxyhydrogen PDE," AIAA Paper 2002-0929, Jan. 2002.

[21]Schauer, F., Stutrud, J., and Bradley, R., "Detonation Initiation Studies and Performance Results for Pulsed Detonation Engine Applications," AIAA Paper 2001-1129, Jan. 2001.

[22]Lasheras, J., Varatharajan, B., Varga, C., and Williams, F., "Studies of Fuel Distribution and Detonation Chemistry for Pulse Detonation Engines," International Symposium on Airbreathing Engines, Paper 2001-1174, Sept. 2001.

[23]Knystautas, R., and Lee, J. H. S., "On the Effective Energy for Direct Initiation of Gaseous Detonations," *Combustion and Flame*, Vol. 27, No. 2, 1976, pp. 221–228.

[24]Kailasanath, K., and Oran, E. S., "Power-Energy Relations for the Direct Initiation of Gaseous Detonations," *Progress in Astronautics and Aeronautics*, Vol. 94, 1984, pp. 38–54.

[25]Benedick, W., Guirao, C., Knystautas, R., and Lee, J. H. S., "Critical Charge for the Direct Initiation of Detonation in Gaseous Fuel/Air Mixtures," *Progress in Astronautics and Aeronautics*, Vol. 106, 1986, pp. 181–202.

[26]Moen, I. O., Thibault, P. A., Funk, J. W., Ward, S. A., and Rude, G. M., "Detonation Length Scales for Fuel-Air Explosives," *Progress in Astronautics and Aeronautics*. Vol. 94, 1984, pp. 55–79.

[27]Sinibaldi, J. O., Brophy, C. M., and Robinson, J. P., "Ignition Effects on Deflagration-to-Detonation Transition Distance in Gaseous Mixtures," AIAA Paper 2000-3590, July 2000.

[28]Lindstedt, R. P., and Michels, H. J., "Deflagration to Detonation Transitions and Strong Deflagrations in Alkane and Alkene Air Mixtures," *Combustion and Flame*, Vol. 76, No. 2, 1989, pp. 169–181.

[29]Hinkey, J. B., Busing, 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.

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

[31]Sanders, S. T., Jenkins, T. P., Baldwin, J. A., Baer, D. S., and Hanson, R. K., "Diode-Laser Absorption Sensor for Measurements in Pulse Detonation Engines," AIAA Paper 2000-0358, Jan. 2000.

[32]Lee, S. Y., Conrad, C., Watts, J., Woodward, R., Pal, S., and Santoro, R. J., "Deflagration to Detonation Transition Study Using Simultaneous Schlieren and OH PLIF Images," AIAA Paper 2000-3217, July 2000.

[33]Santoro, R. J., Conrad, C., Lee, S. Y., and Pal, S., "Fundamental Multi-Cycle Studies of the Performance of Pulse Detonation Engines," International Symposium on Airbreathing Engines, Paper 2001-1171, Sept. 2001.

[34]Cooper, M., Jackson, S., Austin, J. M., Wintenberger, E., and Shepherd, J. E., "Direct Experimental Impulse Measurements for Detonations and Deflagrations," AIAA Paper 2001-3812, July 2001.

[35]Harris, P. G., Farinaccio, R., Stowe, R. A., Higgins, A. J., Thibault, P. A., and Laviolette, J. P., "The Effect of DDT Distance on Impulse in a Detonation Tube," AIAA Paper 2001-3467, July 2001.

[36]Tanguay, V., Kiyanda, C. B., Higgins, A. J., and Lee, J. H. S., "Effect of Transient Gas Dynamic Processes on Impulse of Pulse Detonation Engines," *Proceedings of the 18 ICDERS* [CD-ROM], Univ. of Washington, Seattle, WA, July 2001, Paper 155.

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

[38]Akbar, R., Thibault, P. A., Harris, P. G., Lussier, L. S., Zhang, F., Murray, S. B., and Gerrard, K., "Detonation Properties of Unsensitized and Sensitized JP-10 and Jet-A Fuels in Air for Pulse Detonation Engines," AIAA Paper 2000-3592, July 2000.

[39]Frolov, S. M., Basevich, V. Ya., Belyaev, A. A., and Neuhaus, M. G., "Application of Fuel Blends for Controlling Detonability in Pulsed Detonation Engines," *Gaseous and Heterogeneous Detonations*, edited by G. Roy, S. Frolov, K. Kailasanath, and N. Smirnov, ENAS Publishers, Moscow, 1999, pp. 313–330.

[40]Frolov, S. M., Basevich, V. Ya., and Vasil'ev, A. A., "Dual-Fuel Concept for Advanced Propulsion," *High-Speed Deflagration and Detonation: Fundamentals and Control*, edited by G. D. Roy, S. M. Frolov, D. W. Netzer, and A. A. Borisov, ELEX-KM Publishers, Moscow, 2001, pp. 315–332.

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

[42]Sanders, S. T., Jenkins, T. P., and Hanson, R. K., "Diode-Laser Sensor System for Multi-Parameter Measurements in Pulse Detonation Engine Flows," AIAA Paper 2000-3592, July 2000.

[43]Sanders, S. T., Mattison, D. W., Muruganandam, T. M., and Hanson, R. K., "Multiplexed Diode-Laser Absorption Sensors for Aeropropulsion Flows," AIAA Paper 2001-0412, Jan. 2001.

[44]Mitrofanov, V. V., and Soloukhin, R. I., "On the Instantaneous Diffraction of Detonation Front," *Doklady Akademii Nauk SSSR*, Vol. 159, No. 5, 1964, pp. 1003–1006.

[45]Oppenheim, A. K., and Soloukhin, R. I., "Experiments in Gas Dynamics of Explosions," *Annual Review of Fluid Mechanics*, Vol. 5, 1973, pp. 31–58.

[46]Edwards, D. H., Thomas, G. O., and Nettleton, M. A., "Diffraction of a Planar Detonation in Various Fuel Oxygen Mixtures at an Area Change," *Progress in Astronautics and Aeronautics*, Vol. 75, 1981, pp. 341–357.

[47]Lee, J. H. S., "Dynamic Parameters of Gaseous Detonations," *Annual Review of Fluid Mechanics*, Vol. 16, 1984, pp. 311–336.

[48]Desbordes, D., and Vachon, M., "Critical Diameter of Diffraction for Strong Plane Detonation," *Progress in Astronautics and Aeronautics*, Vol. 106, 1986, pp. 131–143.

[49]Li, C., and Kailasanath, K., "Detonation Transmission and Transition in Channels of Different Sizes," *Proceedings of the Combustion Institute*, Vol. 28, Combustion Inst., Pittsburgh, PA, 2000, pp. 603–609.

[50]Shepherd, J. E., Schultz, E., and Akbar, R., "Detonation Diffraction," Paper 5410, 22nd International Symposium on Shock Waves, Imperial College, London, July 1999.

[51]Sinibaldi, J. O., Brophy, C. M., Li, C., and Kailasanath, K., "Initiator Detonation Diffraction Studies in Pulsed Detonation Engines," AIAA Paper 2001-3466, July 2001.

[52]Brophy, C. M., Netzer, D. W., Sinibaldi, J., and Johnson, R., "Detonation of a JP-10 Aerosol for Pulse Detonation Applications," *High-Speed Deflagration and Detonation: Fundamentals and Control*, edited by G. D. Roy, S. M. Frolov, D. W. Netzer, and A. A. Borisov, ELEX-KM Publishers, Moscow, 2001, pp. 207–222.

[53]Moen, I. O., Sulmistras, A., Thomas, G. O., Bjerketvedt, D., and Thibault, P. A., "Influence of Cellular Regularity on the Behavior of Gaseous Detonation," *Progress in Astronautics and Aeronautics*, Vol. 106, 1986, pp. 220–243.

[54]Thomas, G. O., Edwards, D. H., Lee, J. H., Knystautas, R., Moen, I. O., and Wei, Y. M., "Detonation Diffraction by Divergent Channels," *Progress in Astronautics and Aeronautics*, Vol. 106, 1986, pp. 144–154.

[55]Levin, V. A., Nechaev, J. N., and Tarasov, A. I., "A New Approach to Organizing Operation Cycles in Pulse Detonation Engines," *High-Speed Deflagration and Detonation: Fundamentals and Control*, edited by G. D. Roy, S. M. Frolov, D. W. Netzer, and A. A. Borisov, ELEX-KM Publishers, Moscow, 2001, pp. 223–238.

[56]Smirnov, N. N., Nikitin, V. F., Boichenko, A. P., Tyurnikov, M. V., and Baskakov, V. V., "Deflagration to Detonation Transition in Gases and Its Application to Pulsed Detonation Devices," *Gaseous and Heterogeneous Detonations*, edited by G. Roy, S. Frolov, K. Kailasanath, and N. Smirnov, ENAS Publishers, Moscow, 1999, pp. 65–94.

[57]Smirnov, N. N., Nikitin, V. F., Tyurnikov, M. V., Boichenko, A. P., Legros, J. C., and Shevtsova, V. M., "Control of Detonation Onset in Combustible Gases," *High-Speed Deflagration and Detonation: Fundamentals and Control*, edited by G. D. Roy, S. M. Frolov, D. W. Netzer and A. A. Borisov, ELEX-KM Publishers, Moscow, 2001, pp. 3–30.

[58]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.

[59]Achasov, O. V., and Penyazkov, O. G., "Some Gasdynamic Methods for Control of Detonation Initiation and Propagation," *High-Speed Deflagration and Detonation: Fundamentals and Control*, edited by G. D. Roy, S. M. Frolov, D. W. Netzer, and A. A. Borisov, ELEX-KM Publishers, Moscow, 2001, pp. 31–44.

[60]Brophy, C. M., and Netzer, D. W., "Effect of Ignition Characteristics and Geometry on the Performance of a JP-10/O2 Fueled Pulse Detonation Engine," AIAA Paper 99-2635, July 1999.

[61]Brophy, C. M., Sinibaldi, J. O., Netzer, D. W., and Johnson, R. G., "Operation of a JP-10/Air Pulse Detonation Engine," AIAA Paper 2000-3591, July 2000.

[62]Brophy, C. M., Sinibaldi, J. O., and Damphousse, P., "Initiator Performance for Liquid-Fueled Pulse Detonation Engines," AIAA Paper 2002-0472, Jan. 2002.

[63]Beeson, H., McClenagan, R., Bishop, C., Benz, F., Pitz, W., Westbrook, C., and Lee, J., "Detonability of Hydrocarbon Fuels in Air," *Progress in Astronautics and Aeronautics*, Vol. 133, 1989, pp. 19–36.

[64]Murray, S., and Lee, J., "The Influence of Yielding Confinement o Large-Scale Ethylene-Air Detonations," *Progress in Astronautics and Aeronautics*, Vol. 94, 1984, pp. 80–103.

[65]Chang, E. J., and Kailasanath, K., "Shock Wave Interactions with Particles and Fuel Droplets," AIAA Paper 2000-0319, Jan. 2000.

[66]Li, S. C., Varatharajan, B., and Williams, F. A., "Chemistry of JP-10 Ignition," *AIAA Journal*, Vol. 39, No. 12, 2001, pp. 2351–2356.

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

[68]Cambier, J. L., "Preliminary Modeling of Pulse Detonation Rocket Engines," AIAA Paper 99-2659, June 1999.

[69]Ebrahimi, H. B., and Merkle, C. L., "A Numerical Simulation of the Pulse Detonation Engine with Hydrogen Fuels," AIAA Paper 99-2259, June 1999.

[70]Li, C., Kailasanath, K., and Patnaik, G., "A Numerical Study of Flow Field Evolution in a Pulse Detonation Engine," AIAA Paper 2000-0314, Jan. 2000.

[71]Kailasanath, K., and Patnaik, G., "Performance Estimates of Pulsed Detonation Engines," *Proceedings of the Combustion Institute*, Vol. 28, Combustion Inst., Pittsburgh, PA, 2000, pp. 595–601.

[72]Ebrahimi, H. B., Mohanraj, R., and Merkle, C. L., "Multi-Level Analysis of Pulsed Detonation Engines," AIAA Paper 2000-3589, July 2000.

[73]Eidelman, S., Sharov, D., and Book, D., "Aerothermodynamics of Pulsed Detonation Engines," AIAA Paper 2000-3892, July 2000.

[74]Scott, T., and Isaac, K. M., "Utilization of Pressure Waves Interaction to Investigate PDE Internal Flow Paths," AIAA Paper 2001-3612, July 2001.

[75]Zhang, Z.-C., Yu, S. T. J., He, H., and Jorgenson, P. C. E., "Direct Calculations of Plume Dynamics of a Pulse Detonation Engine by the Space-Time CE/SE Method," AIAA Paper 2001-3614, July 2001.

[76]Allgood, D., Gutmark, E., and Katta, V., "Effects of Exit Geometry on the Performance of a Pulse Detonation Engine," AIAA Paper 2002-0613, Jan. 2002.

[77]Kailasanath, K., "Verification and Validation of Pulsed Detonation Engine Computations," Combustion Inst., Paper 142, March 2001.

[78]Jenkins, T. P., Sanders, S. T., Kailasanath, K., Li, C., and Hanson, R. K., "Diode Laser-Based Measurements for Model Validation in Pulse Detonation Flows," *Proceedings of the 25th JANNAF Airbreathing Propulsion Meeting*, JSC CD-05, CPIA, Columbia, MD, 2000.

[79]Li, C., and Kailasanath, K.,"A Numerical Study of Reactive Flows in Pulse Detonation Engines," AIAA Paper 2001-3933, July 2001.

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

[81]Cambier, J. L., and Tegner, J. K., "Strategies for Pulsed Detonation Engine Performance Optimization," *Journal of Propulsion and Power*, Vol. 14, No. 4, 1998, pp. 489–498.

[82]Zitoun, R., and Desbordes, D., "Propulsive Performances of Pulsed Detonations," *Combustion Science and Technology*, Vol. 144, 1999, pp. 93–114.

[83]Mohanraj, R., and Merkle, C. L., "A Numerical Study of Pulse Detonation Engine Performance," AIAA Paper 2000-0315, Jan. 2000.

[84]Talley, D., and Coy, E., "The Constant Volume Limit of Pulsed Propulsion for a Constant g Ideal Gas," AIAA Paper 2000-3216, July 2000.

[85]Kentfield, J. A. C., "Fundamentals of Idealized Air-Breathing Pulse-Detonation Engines," *Journal of Propulsion and Power*, Vol. 18, No. 1, 2002, pp. 77–83.

[86]Fong, K. K., and Nalim, M. R., "Gas Dynamic Limits and Optimization of Pulsed Detonation Static Thrust," AIAA Paper 2000-3471, July 2000.

[87]Paxson, D. E., "A Performance Map for Ideal Air Breathing Pulse Detonation Engines," AIAA Paper 2001-3465, July 2001.

[88]Povinelli, L. A., "Impact of Dissociation and Sensible Heat Release on Pulse Detonation and Gas Turbine Engine Performance," International Symposium on Airbreathing Engines, Paper 2001-1212, Sept. 2001.

[89]Povinelli, L., Lee, J. H., and Anderberg, M., "Role of Air-Breathing Pulse Detonation Engines in High Speed Propulsion," International Astronautical Federation, Paper 01-S.5.01, Oct. 2001.

[90]Wu, Y., Ma, F., and Yang, V., "System Performance and Thermodynamic Cycle Analysis of Pulse Detonation Engines," International Symposium on Airbreathing Engines, Paper 2001-1210, Sept. 2001.

[91]Heiser, W. H., and Pratt, D. T., "Thermodynamic Cycle Analysis of Pulse Detonation Engines," *Journal of Propulsion and Power*, Vol. 18, No. 1, 2002, pp. 68–76.

[92]Kailasanath, K., Patnaik, G., and Li, C., "On Factors Controlling the Performance of Pulsed Detonation Engines," *High-Speed Deflagration and Detonation: Fundamentals and Control*, edited by G. D. Roy, S. M. Frolov, D. W. Netzer, and A. A. Borisov, ELEX-KM Publishers, Moscow, 2001, pp. 193–206.

[93]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.

[94]Poinsot, T., and Lele, S. K., "Boundary Conditions for Direct Simulations of Compressible Viscous Flows," *Journal of Computational of Physics*, Vol. 101, 1992, pp. 104–129.

[95]Zhdan, S. A., Mitrofanov, V. V., and Sychev, A. I., "Impulse Produced by Gas Detonation in Open Chamber," *Proceedings of the Zeldovich Memorial*, edited by S. M. Frolov, Russian Section of the Combustion Inst., Vol. 2, 1994, pp. 422–425.

[96]Wintenberger, E., Austin, J. M., Cooper, M., Jackson, S., and Shepherd, J. E., "An Analytical Model for the Impulse of a Single-Cycle Pulse Detonation Engine," AIAA Paper 2001-3811, July 2001.

[97]Falempin, F., Bouchaud, D., Forrat, B., Desbordes, D., and Daniau, E., "Pulsed Detonation Engine: Possible Application to Low Cost Tactical Missile and to Space launcher," AIAA Paper 2001-3815, July 2001.

[98]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.

[99]Zhdan, S. A., Mitrofanov, V. V., and Sychev, A. I., "Reactive Impulse from the Explosion of a Gas Mixture in a Semiinfinite Space," *Combustion, Explosion, and Shock Waves*, Vol. 30, No. 5, 1994, pp. 657–663.

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

[101]Brophy, C. M., Sinibaldi, J., and Netzer, D. W., "Effects of Fuel Distribution on Pulse Detonation Engine Operation and Performance," International Symposium on Airbreathing Engines, Paper 2001-1173, Sept. 2001.

[102]Bouchaud, D., Forrat, B., Piton, D., and Yvart, P., "AEROSPATIALE and CELERG Investigations on Pulse Detonation Propulsion," AIAA Paper 99-2658, June 1999.

[103]Li, C., and Kailasanath, K., "Performance Analysis of Pulse Detonation Engines with Partial Fuel Filling," AIAA Paper 2002-0610, Jan. 2002.

[104]Daniau, E., Zitoun, R., and Desbordes, D., "Effects of Nozzles of Different Length and Shape on Propulsive Performance of Pulsed Detonation Engines," *High-Speed Deflagration and Detonation: Fundamentals and Control*, edited by G. D. Roy, S. M. Frolov, D. W. Netzer, and A. A. Borisov, ELEX-KM Publishers, Moscow, 2001, pp. 251–262.

[105]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.

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

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

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

[109]Ebrahimi, H. B., Mohanraj, R., and Merkle, C. L., "Modeling of Multi-Tube Pulse Detonation Engine Operation," AIAA Paper 2001-3813, July 2001.

[110]Butuk, N., Ye, F., Huque, Z., and Lynch, D., "CFD Simulations of a Novel Multi-Tube Pulse Detonation Engine Inlet Concept," AIAA Paper 99-2240, June 1999.

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

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

[113] Mullagiri, S., Gustavsson, J., and Segal, C., "Modeling of Air Intake and Engine Interaction in Pulse Detonation Engine," International Symposium on Airbreathing Engines, Paper 2001-1211, Sept. 2001.

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

[115] McManus, K., Furlong, E., Leyva, I., and Sanderson, S., "MEMS-Based Pulse Detonation Engine for Small-Scale Propulsion Applications," AIAA Paper 2001-3469, July 2001.

[116] Mawid, M. A., Park, T. W., and Sekar, B., "Performance Analysis of a Pulse Detonation Device As an Afterburner," AIAA Paper 00-3474, July 2000.

[117] Mawid, M. A., and Park, T. W., "Towards Replacement of Turbofan Engines Afterburners with Pulse Detonation Devices," AIAA Paper 2001-3470, July 2001.

[118] Litchford, R. J., Thompson, B. R., and Lineberry, J. T., "Pulse Detonation Magnetohydrodynamic Power," *Journal of Propulsion and Power*, Vol. 16, No. 2, 2000, pp. 251–262.

[119] Razi Nalim, M., and Izzy, Z. A., "Rotary Ejector Enhanced Pulse Detonation System," AIAA Paper 2001-3613, July 2001.

[120] Munipalli, R., Shanker, V., Wilson, D. R., and Lu, F. K., "Preliminary Design of a Pulsed Detonation Based Combined Cycle Engine," International Symposium on Airbreathing Engines, Paper 2001-1213, Sept. 2001.

[121] Wilson, D. R., Lu, F. K., Kim, H., and Munipalli, R., "Analysis of a Pulsed Normal Detonation Wave Engine Concept," AIAA Paper 2001-1784, June 2001.

[122] Falempin, F., Bouchaud, D., and Daniau, E., "Pulse Detonation Engine: Towards a Tactical Missile Application," AIAA Paper 2000-3473, July 2000.

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

[124] Mueller, D., Bratkovich, T., Lupkes, K., Henderson, S., Williams, J., and Bussing, T., "Recent ASI Progress in Pulse Detonation Rocket Engine Hardware Development," AIAA Paper 99-2886, June 1999.

[125] Frankey, B., Schauer, F., Bradley, R., and Hoke, J., "Evaluation of a Hybrid-Piston Pulsed Detonation Engine," AIAA Paper 2002-0474, Jan. 2002.

[126] Hoke, J., Bradley, R., Stutrud, J., and Schauer, F., "Integration of a Pulsed Detonation Engine with an Ejector Pump and with a Turbo-Charger as Methods to Self-Aspirate," AIAA Paper 2002-0615, Jan. 2002.

[127] Kaemming, T., "Integrated Vehicle Comparison of Turbo-Ramjet Engine and Pulsed Detonation Engine (PDE)," Gas Turbine and Aeroengine Congress and Exhibition, Paper 2001-GT-451, June 2001.

G. M. Faeth
Editor-in-Chief