Review of Propulsion Applications and Numerical Simulations of the Pulsed Detonation Engine Concept

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Here we review experimental and computational studies of the pulsed detonation engine concept (PDEC) and present results of our recent numerical study of this concept. The PDEC was proposed in the early 1940s for small engine applications; however, its potential was never realized due to a complicated, unsteady operation regime. In this study, we demonstrate the use of current advances in numerical simulation for the analysis of the PDEC. The high-thrust/engine volume ratio obtained in our simulations demonstrates promising potential of the pulsed detonation engine concept.

Introduction

EARLY developments of engine technology leading to practical propulsion engines were almost completely associated with steady-state engine concepts. Unsteady concepts, which initially appeared promising, never evolved from the conceptual state and have remained for the most part unexplored. The early work in unsteady propulsion suffered from a lack of appropriate analytical and design tools, a condition which seriously impeded the advancement of the unsteady concepts to a practical stage.

In this paper, we review the historical development of unsteady propulsion by concentrating on the particular concept of the intermittent detonation engine, and discuss current research activities in this area. A review of the literature[1-24] reveals that a significant body of experimental and theoretical research exists in the area of unsteady propulsion. However, this research has not been extended to the point where a conclusive quantitative comparison can be made between impulsive engine concepts and steady-state concepts. For example, the analysis given in Refs. 8–11 of the performance of a detonation engine concept includes neither frequency dependence nor analysis of losses due to multicycle operation. A new generation of analytical and computational tools exists today and allows us to revisit and analyze such issues with a high degree of confidence. Numerical simulation has developed to the state where it can now provide time-dependent two- and three-dimensional modeling of complex internal flow processes[20,24,25] and will eventually result in tools for systematically analyzing and optimizing engineering design. In addition to a review of applications of the pulsed detonation engine concept (PDEC), we will report results of a numerical study of an air-breathing detonation engine. This study was performed using new unsteady computational fluid dynamics (CFD) tools that we will also describe.

Our paper is structured as follows: 1) historical review of the pulsed detonation development efforts; 2) description of the basic phenomenology of the air-breathing pulsed detonation engine concept; 3) description of the mathematical formulation and new numerical scheme used to simulate the problem; 4) discussion of the simulation results; and 5) conclusions.

Presented as Paper 89-2446 at the AIAA/ASME/ASEE/SAE 25th Joint Propulsion Conference, Monterey, CA, July 10–12, 1989; received Sept. 8, 1989; revision received April 12, 1990. This paper is declared a work of the U.S. Government and is not subject to copyright protection in the United States.

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Historical Review

Constant-Volume Combustion

From the very early development of jet-propulsion engines, it was known that an engine based on a constant-volume combustion process achieves higher thermodynamics efficiency than a constant pressure engine. This follows from a thermodynamic analysis of the engine cycle.[1]

Constant-volume combustion was used in gas turbine engines at the beginning of this century, and the first gas turbine engines in commercial use were based on the constant-volume cycle. Jet-propulsion engines were one of the applications of the constant volume cycle (or explosion cycle) which was explored in the late 1940s.[2] Although the explosion cycle operates at a larger pressure variation in the combustion chamber than in a pulse jet,[3,4] the cycle actually realized in these engines was not a fully constant-volume one since the combustion chamber was open-ended.[2] In Ref. 2, the maximum pressure ratio measured in an explosion cycle engine was 3:1, whereas the pressure ratio for the same mixture under the assumption of a constant-volume cycle would be 8:1. Also, this engine was limited by the available frequency of cycles, which in turn was limited by the reaction rate. A simple calculation[2] showed that if the combustion time could be reduced in this engine from 0.006–0.003 s, the thrust per pound of mixture would increase 100%. Thus, the explosion-cycle engine has two main disadvantages:

1) Constrained volume combustion (as distinguished from constant-volume combustion) does not take full advantage of the pressure rise characteristic of the constant-volume combustion process.

2) The frequency of the explosion cycle is limited by the reaction rate, which is only slightly higher than the deflagrative combustion rate.

The main advantage of the constant-pressure cycle is that it leads to engine configurations with the steady-state processes of injection of the fuel and oxidizer, combustion of the mixture, and expansion of the combustion products. These stages can be easily identified and the engine designer can optimize them on the basis of relatively simple steady-state considerations.

At the same time, an engine based on constant-volume combustion will have an intermittent mode of operation, which may complicate its design and optimization. We are interested in the question of whether this complication is worth the potential gains in engine efficiency.

Pulsed Detonation Engine as an Ultimate Constant-Volume Combustion Concept

The detonation process, due to the very high rate of reaction, permits construction of a propulsion engine in which the constant-volume process can be fully realized. In detonative combustion, the strong shock wave, which is part of the detonation wave, acts like a valve between the detonation products and the fresh charge. The speed of the detonation wave is about two orders of magnitude higher than the speed of a typical deflagration. This allows the design of propulsion engines with a very high power density. Usually, each detonation is initiated separately by a fully controlled ignition device, and the cycle frequency can be changed over a wide range of values. There is only an upper limit for the detonation cycle frequency. This limit is determined by the time it takes to refill the detonation chamber with the fresh combustible mixture. This in turn will depend on chamber geometry and the external flow parameters. In our study, we have established that detonation frequencies of 200–250 Hz appear to be feasible. At the same time, the same PDEC engine can operate at very low detonation frequency with thrust almost linearly proportional to the frequency. This also means that a device based on a detonative combustion cycle can be scaled, and its operating parameters can be modified for a range of required output conditions. There have been numerous attempts to take advantage of detonative combustion for engine applications. In the following, we give a description of the most relevant past experimental and analytical studies of the detonation engine concept.

Hoffmann's Report

The first reported work on intermittent detonation is attributed to Hoffmann[5] in 1940. He operated an intermittent detonation test stand with acetylene-oxygen and benzine-oxygen mixtures. The addition of water vapor was used to prevent the highly sensitive acetylene-oxygen mixture from premature detonation. Hoffmann[5] indicated the importance of the spark plug location in reference to tube length and diffuser length. It was found that a continuous injection of the combustible mixture leads to only a narrow range of ignition frequencies that will produce an intermittent detonation cycle. These frequencies are governed by the time required for the mixture to reach the igniter, the time of transition from deflagration to detonation, and the time of expansion of the detonation products. Hoffmann attempted to find the optimum cycle frequency experimentally. It was discovered that detonation-tube firing occurred at lower frequencies than the spark-plug energizing frequencies, indicating that the injection flow rate and ignition were out of phase. World War II prevented further work by Hoffmann and co-workers.

Nicholls' Experiments

A substantial effort in intermittent detonation engine research was done by a group headed by Nicholls[6-10] of the University of Michigan beginning in the early 1950s. The most relevant work concerns a set of experiments carried out in a 6-ft-long detonation tube.[6] The schematics of the detonation-tube experiments test rig used by Nicholls and co-workers are shown in Fig. 1. The detonation tube was contructed from a 1-in.-i.d. stainless-steel tube. The fuel and oxidizer were injected under pressure from the left end of the tube and ignited at the 10-in. distance downstream. The tube was mounted on a pendulum platform that was suspended by support wires. Thrust for single detonations was measured by detecting tube (platform) movement relative to a stationary pointer. For multicycle detonations, thrust measurement was achieved by mounting the thrust end of the tube to the free end of the cantilever beam. In addition to direct thrust measurements, the temperature on the inner wall of the detonation tube was measured.

Fuel mixtures of hydrogen/oxygen, hydrogen/air, acetylene-oxygen, and acetylene-air were used. The gaseous oxidizer and fuel were continuously injected at the closed end wall of the detonation tube and three fixed flow rates were used. Under these conditions, the only parameters that could be varied were the fuel/oxidizer ratio and frequency of ignition. A maximum gross thrust of ≈ 3.2 lb was measured in hydrogen/air mixture at the frequency of ≈ 30 detonations/s. The most promising results were demonstrated for the hydrogen/air mixture, where a fuel specific impulse of $I_{sp} = 2100$ s was reached. The maximum frequency of detonations obtained in all experiments was 35 Hz. The temperature measurements on the inner wall showed that for the highest frequency of detonations the temperature did not exceed 800°F.

In their later work,[8-10] the University of Michigan group concentrated on development of the rotating detonation wave rocket motor. No further work on the pulsed detonation cycle was pursued.

Krzycki's Experiments

In a setup somewhat similar to Nicholls', Krzycki[11] performed an experimental investigation of intermittent detonations with frequencies up to 60 cps. An attempt was also made to analyze the basic phenomena using unsteady gas dynamic theory. Krzycki's attempt to analyze the basic phenomena relied on wave diagrams to trace characteristics, assumptions of isentropic flow for detonation and expansion, and incompressible flow for mixture injection processes. The most convincing data from the experiments are the measurement of thrust for a range of initiation frequencies and mixture flow rates. Unfortunately, no direct pressure measurement in the device are reported so that only indirect evidence exists of the nature of the process observed.

The basic test stand used by Krzycki is very similar to that used by Nicholls et al.[6] The length of the detonation tube and internal diameter were exactly the same as those in Nicholls' experiments. A propane/air mixture was continuously injected through reversed-flow diffuser for better mixing and

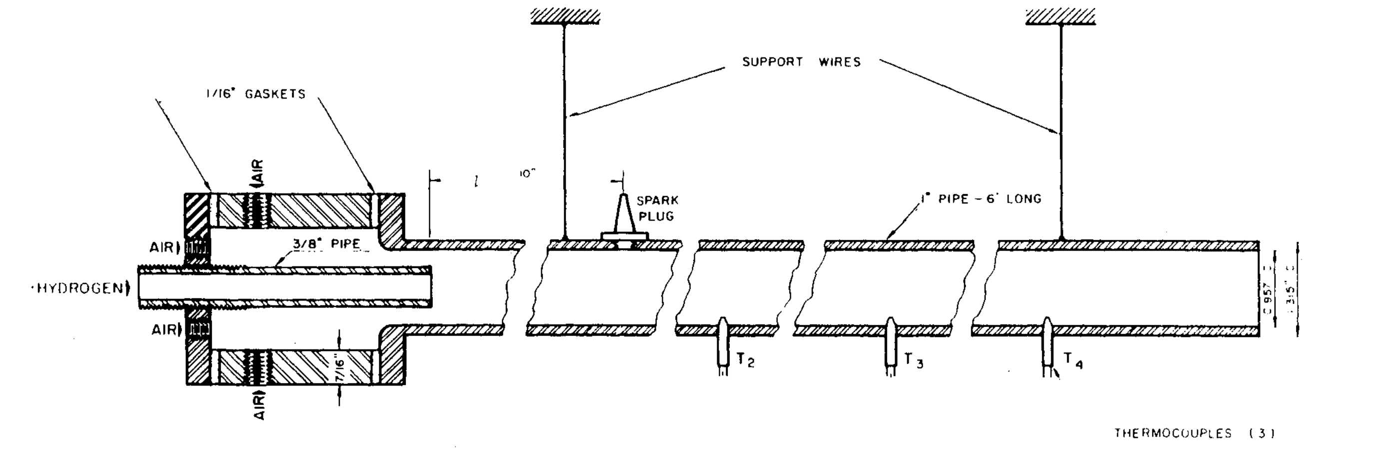


Fig. 1 Detonation tube used in experiments by Nicholls et al.

ignited at the 25-cm distance from the injection point by an automobile spark plug. The spark frequency was varied from 1-60 Hz. The spark plug power output was varied inversely with the initiation frequency and at the frequency of 60 Hz was only 0.65 J. This fact alone eliminated the possibility of direct initiation of the detonation wave by the spark and consequently all of the experiments were performed in the region dominated by transition from deflagration to detonation. According to experimental data and theory,[12] for direct initiation of a mixture of propane/air at the detonability limits, an energy release on the order of 10^6 J is required. Thus, the required deflagration-detonation transition region length would have been prohibitively large for the propane/air mixture. It follows that in all of the experiments a substantial part of the process was deflagrative. This resulted in low efficiency and negligible thrust. Krzycki repeated the experiments of Nicholls using exactly the same size detonation tube and basically the same rates of injection of the detonatable mixture. Krzycki's experimental results are very well-documented, giving enough information to deduce a clear picture of the physical processes occurring in the tube. A conclusion, arrived at by the author, was that thrust was possible from such a device but practical applications did not appear promising. It is unfortunate that, possibly based on Krzycki's extensive but misleading results, all experimental work related to the pulsed detonation engine concept stopped at this time.

Work Reported in Russian Sources on Pulse Detonation Devices

A review of the Russian literature has not uncovered work concerning applications of pulsed detonation devices to propulsion. However, there are numerous reports of applications of such devices for producing nitrogen oxide[13] (an idea proposed in the 1940s by Zeldovich to use detonation for binding nitrogen directly from air to produce fertilizers) and as rock crushing devices.[14]

Korovin et al.[13] provide a most interesting account of the operation of a commercial detonation reactor. The main objective of this study was to examine the efficiency of thermal oxidation of nitrogen in an intermittent detonative process as well as an assessment of such technological issues as the fatigue of the reactor parts exposed to the intermittent detonation waves over a prolonged time. The reactor consisted of a tube with an inner diameter of 16 mm and length 1.3 m joined by a conical diffuser to a second tube with an inner diameter of 70 mm and length 3 m. The entire detonation reactor was submerged in running water. The detonation mixture was introduced at the end wall of the small tube. Methane, oxygen, and nitrogen comprised the mixture composition and the mixture ratios were varied during the continuous operation of the reactor. The detonation wave velocity was measured directly by piezoelectric sensors placed in the small and large tubes. The detonation initiation frequency in the reactor was 2-16 Hz. It is reported that the apparatus operated without significant changes for 2000 h.

Smirnov and Boichenko[14] studied intermittent detonations of a gasoline/air mixtures in a 3-m-long and 22-mm-i.d. tube operating in the 6-8 Hz ignition frequency range. The main motivation of this work was to improve the efficiency of a commercial rock-crushing apparatus based on intermittent detonations of the gasoline/air mixtures.[15] The authors investigated the dependence of the length of the transitional region from deflagration to detonation on the initial temperature of the mixture.

As a result of the information contained in the Soviet reports, it can be concluded that reliable commercial devices based on intermittent detonations can be constructed and operated.

Development of the Blast Propulsion System at JPL

Back,[16] Varsi et al.,[17] Kim et al.,[18] and Back et al.[19] at the Jet Propulsion Laboratory (JPL) studied the feasibility of a rocket thruster powered by intermittent detonations of solid explosive. The main application foreseen by the authors is propulsion in dense or high-pressure atmospheres of certain solar system planets. The JPL work was directed at very specific applications; however, the studies[17-19] addressed some key issues of devices using unsteady processes such as propulsion efficiency. The JPL studies have important implications to pulsed detonation propulsion systems.

Reference 19 gives the basic description of the test stand used. In this work, a data sheet type C explosive was detonated inside a small detonation chamber attached to nozzles of various length and geometry. The nozzles, complete with firing plug, were mounted in a containment vessel that could be pressurized with the mixture of various inert gases from vacuum to 70 atm. The apparatus measured directly the thrust generated by single detonations of a small amount of solid explosive charge expanding into conical or straight nozzles. Thrust and specific impulse were measured by a pendulum balance system.

Results obtained from an extensive experimental study of the explosively driven rocket have led to the following conclusions. First, rockets with long nozzles show increasing specific impulse with increasing ambient pressure in carbon dioxide and nitrogen. Short nozzles, on the other hand, show that specific impulse is independent of ambient pressure. Most importantly, most of the experiments obtained a relatively high specific impulse of 250 s and larger. This result is all the more striking since the detonation of a solid explosive yields a relatively low energy release of approximately 1000 cal/g compared with 3000 cal/g obtained in hydrogen/oxygen combustion. Thus, it can be concluded that the total losses in a thruster based on unsteady expansion are not prohibitive and, in principle, very efficient propulsion systems operating on intermittent detonations are possible.

Detonation Engine Studies at Naval Postgraduate School

A modest exploratory study of a propulsion device utilizing detonation phenomena was conducted at the Naval Postgraduate School (NPS).[20-23] During this study, several fundamentally new elements were introduced to the concept distinguishing the new device from previous ones.

First, it is important to note that the experimental apparatus constructed by Helman et al.[22] showed the first successful self-aspirating, air-breathing detonation device. Intermittent detonation frequencies of 25 Hz were obtained. This frequency was in phase with the fuel-mixture injection through timed fuel-valve opening and spark discharge. The feasibility of intermittent injection was established. Pressure measurements showed conclusively that a detonation process occurred at the frequency chosen for fuel injection. Furthermore, self-aspiration was shown to be effective. Finally, the effectiveness of a primary detonation as a driver for the main detonation was clearly demonstrated. Although the NPS studies were abbreviated, many of the technical issues considered to be essential for efficient intermittent detonation propulsion were addressed with positive results.

Simulations of Pulsed Detonation Engine Cycle at NASA Ames Research Center

Recently, Cambier and Adelman[24] carried out numerical simulations of a pulsed detonation engine cycle taking into account finite-rate chemistry. Unfortunately, the simulations were restricted to a quasi-one-dimensional model. The configuration considered had a 6-cm-i.d., 50-cm-long main chamber that was attached to a 43-cm-long diverging nozzle. It was assumed that a stoichiometric mixture of hydrogen/air at 3.0 atm is injected from an inlet on the closed end wall of the detonation chamber. Under these conditions, Cambier and Adelman estimated a large range of possible detonation frequencies of engine operation up to 667 Hz. The origin of this estimate is not clear from their work since, according to their simulations, the detonation, expansion, and fresh charge fill requires 2.5 ms. This value leads to a maximum frequency of

400 Hz. The simulated engine performance yielded a large average thrust of ≈ 4000 N and an unusually high specific impulse of 6507 s. These simulations were the first to demonstrate the use of modern CFD methods to address the technical issues associated with unsteady pulsed detonation concepts.

In the remaining sections, we discuss a particular propulsion concept based on the results of the experiments of Helman et al.[22] and describe a computational study of its performance characteristics. The unsteady numerical scheme used for the study made use of unique simulation techniques; the key ingredients of these techniques are also described.

Generic Pulsed Detonation Engine

The generic device we consider here is a small cylindrical engine, 15 cm long and 15 cm in diameter. The combustible gas mixture is injected at the closed end of the detonation chamber and a detonation wave propagates through the mixture. The size of the engine suggests a small payload, but the concept can be extended to larger payloads simply by scaling up the size of the detonation chamber and possibly combining a number of engines into one large propulsion engine. A key issue in the pulsed detonation engine concept is the design of the main detonation chamber. The detonation chamber geometry determines the propulsion efficiency and the duration of the cycle (frequency of detonations). Since the fresh charge for the generic engine is supplied from the external flowfield, the efficiency of the engine depends on the interaction of the surrounding flow with the internal flow dynamics. The range of the physical processes requiring simulation in order to model the complex flow phenomena associated with the detonation engine performance is very broad. A partial list is as follows:

1) Initiation and propagation of the detonation wave inside the chamber.

2) Expansion of the detonation products from the chamber into the airstream around the chamber at flight Mach numbers.

3) Reverse flow from the surrounding air into chamber resulting from overexpansion of the detonation products.

4) Pressure buildup in the chamber due to reverse flow. The flow pattern inside the chamber during postexhaust pressure buildup determines the strategy for mixing the next detonation charge.

5) Strong mutual interaction between the flow processes inside the chamber and flow around the engine.

All of these processes are interdependent and their timing is crucial to the engine efficiency. Thus, unlike simulations of steady-state engines, the phenomena described above cannot be evaluated independently.

The need to resolve the flow inside the chamber accounting for nozzles, air inlets, etc., and at the same time resolve the flow around the engine, where the flow regime varies from high subsonic, locally transonic, and supersonic, makes it a challenging computational problem.

The main issue is to determine the timing of the air intake for the fresh gas charge. It is sufficient to assume inviscid flow for the purpose of simulating the expansion of the detonation products and fresh gas intake. In the following, we present the first results of an inviscid simulation of the detonation cycle in a cylindrical chamber. First, we describe our computational method for solving the time-dependent Euler equations used in the study.

Unsteady Euler Solver

A new second-order algorithm for solving the Euler equations on an unstructured grid was used in our study of the detonation concept. The approach is based on first- and second-order Godunov methods. The method leads to an extremely efficient and fast flow solver that is fully vectorized and easily lends itself to parallelization. The low memory requirements and speed of the method are due to the use of a unique data structure.

Until recently most CFD simulations were carried out with logically structured grids. Vectorization and/or parallelization did not present a problem. The increased need for simulation of flow phenomena in the vicinity of complex geometrical bodies and surfaces has led to the development of CFD codes for logically unstructured grids. The most successful of these unstructured grid codes are based on finite elements or finite volume methods. For an unstructured grid in two dimensions, the computational domain is usually covered by triangles, and the indices of the arrays containing the values of the hydrodynamic flow quantities are not related directly to the actual geometric location of a node. The calculations performed on unstructured grids evolve around the elemental grid shape (e.g., the triangle for two-dimensional problems), and there is no obvious pattern to the order in which the local integrations should be performed. Explicit integration of hydrodynamic problems on an unstructured grid requires that a logical substructure should be created which identifies the locations in the global arrays of all of the local quantities necessary for the integration of one element. This usually results in a large price in computational efficiency, in memory requirements, and in code complexity. As a consequence, vectorization for the conventional unstructured grid methods has concentrated on rearrangement of the data structure in a manner such that these locally centered data structures appear as global arrays. This can be done to some extent using machine dependent gather-scatter operations.[25,26] Additional optimization can be achieved using localization and search algorithms. However, these methods are complex and result in marginal improvement. Most optimized unstructured codes to date run considerably slower and require an order of magnitude more memory per grid cell than their structured counterparts. Parallelization of the conventional unstructured codes is even more difficult, and there is very little experience with unstructured codes on massively parallel computers.

The method we have developed overcomes these difficulties and results in codes with speed and memory requirements comparable to those found in structured grid codes. Moreover, the ability to construct grids with arbitrary resolution leads to a flexibility in dealing with complex geometries not attainable with structured grids. The essence of the method is based on an independent flux calculation across the edges of a dual baricentric grid, followed by node integration. This approach is order independent. Below we give the essential details of our algorithm; a complete description follows later.

Basic Integration Algorithm

We begin by describing the first-order Godunov method for the system of two-dimensional (axisymmetric) Euler equations written in conservation law form as

$$\frac{\partial Q}{\partial t} + \frac{\partial F}{\partial x} + \frac{\partial G}{\partial r} = -\frac{1}{r}C \qquad (1)$$

where

$$Q = \begin{bmatrix} \rho \\ \rho u \\ \rho v \\ e \end{bmatrix}, \qquad F = \begin{bmatrix} \rho u \\ \rho u^2 + p \\ \rho uv \\ (e+p)u \end{bmatrix}$$

$$G = \begin{bmatrix} \rho v \\ \rho vu \\ \rho v^2 + p \\ (e+p)v \end{bmatrix}, \qquad C = \begin{bmatrix} \rho v \\ \rho vu \\ \rho v^2 \\ (e+p)v \end{bmatrix}$$

Here u and v are the x and r velocity vector components, p the pressure, ρ the density, and e the total energy of the fluid per unit volume. It is assumed that a mixed (initial conditions, boundary conditions) problem is properly posed for the set,

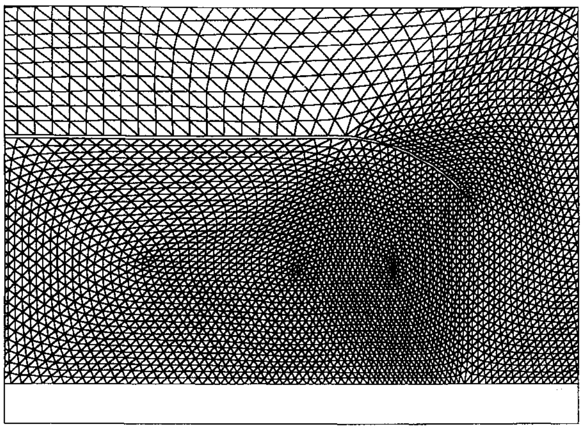


Fig. 2a Computational domain and grid used in simulation of PDEC operation.

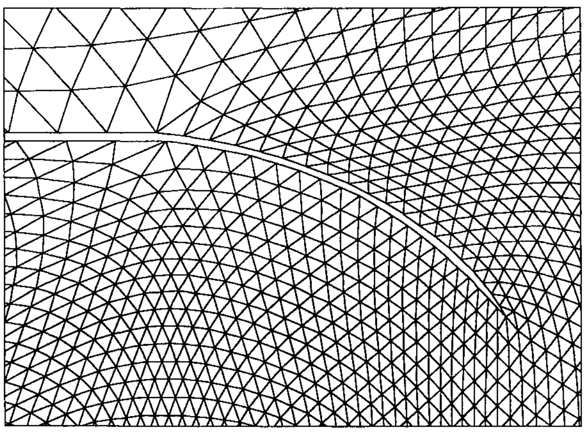


Fig. 2b Enlargement of computational grid in the vicinity of the PDEC nozzle.

Eq. (1), and that an initial distribution of the fluid parameters is given at $t = 0$ and some boundary conditions defining a unique solution are specified on the boundary of the computational domain.

We look for a solution of the system of equations represented by Eq. (2) in the computational domain covered by an unstructured grid. As an example, Fig. 2a shows the unstructured triangular grid used in the pulsed detonation engine simulation. Here most of the computational effort is committed to the resolution of the flow inside the engine detonation chamber and in the immediate vicinity of the nozzle. In Fig. 2b, an enlargement of the nozzle region is shown, illustrating the ability to represent geometry of arbitrary complexity and with localized resolution.

Figure 3 displays a fragment of the computational domain with the corresponding dual grid. The secondary or dual grid is formed by connecting the baricenters of the primary mesh, thus forming finite polygons around the primary vertices.

We have found, as have others,[27] that the best practical representation of the integration volume is obtained when the dual grid is formed by connecting baricenters of the triangles. Integration by the Godunov method[28] can be divided into two basic steps: 1) calculation of the fluxes at the edges of the secondary grid using solutions of a set of one-dimensional Riemann problems; and 2) integration of the system of partial differential equations, which amounts to addition of all of the fluxes for every polygon at a particular time step.

To define the fluxes for the grid shown in Fig. 3 at every edge of the main grid, it is necessary to solve the corresponding Riemann problem. For example, to define the flux at the edge *ab*, we solve the Riemann problem between points A and B. The solution of this problem is in coordinates local to the

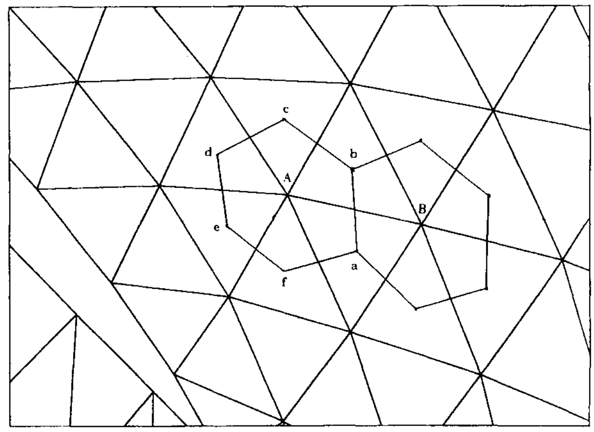


Fig. 3 The primary (triangles) and secondary (polygons) unstructured grids.

edge of the dual grid *ab* so that the tangential component of velocity will be directed along this edge (*ab*). Implementation of our approach requires maintaining strict consistency when defining the "left" and "right" states for the Riemann problems at the edges *ab, bc, cd, de, ef,* and *fa*. For this reason, we define not only the location of the vertices and lengths of the edges but also the direction of the edges with respect to the primary grid. For the clockwise integration pattern in the same polygon, point A will be the "right" state for all of the Riemann problems related to this point, and the neighbor will represent the "left" side of the diaphragm.

It is easy to see that the flux calculation is based on information at only two nodes and requires single geometrical parameters defining the edge of the secondary grid that dissects the line connecting the two points. Thus, we can calculate all of the values needed for flux calculation in one loop over all edges of the primary grid without any details related to the geometrical structures that these edges form. This in turn assures parallelization or vectorization of the algorithm for the bulk of the calculations involving the Riemann solver that provides the first-order flux. The only procedure not readily parallelizable is the integration of the fluxes for the flow variables at the vertices of the grid. Here we use the "edge coloring" technique that allows us to split the flux addition loop into seven or eight loops for edges of different color. Each of these loops is usually large enough not to impair vectorization. At this stage, all of the fluxes are added with their correct sign corresponding to the chosen direction of integration within the cell. The amount of calculation required here is minimal since the fluxes are known and need only to be multiplied at each time step by a simple factor and added to the vertex quantity.

Second-Order Integration Algorithm

The second-order solver is constructed along lines similar to that of the first-order method. At each cell edge, the Riemann problem is solved for some specified pair of left and right conditions. The solution to this Riemann problem is then used in the calculation of fluxes that are added later to advance to the next integration step. The extension to second-order is achieved by using extrapolation in space and time to obtain time-centered left and right-limiting values as inputs for the Riemann problem. The basic implementation of the method of calculation of second-order accurate fluxes is fundamentally the same as for one-dimensional cases. The only difference is in the method of obtaining linear extrapolation of the flow variables as a first guess of their value at the edges of the dual grid. To obtain the first guess, we need to know the gradient of some gasdynamical parameter U at the vertices of the primary mesh. The value of ∇U can be evaluated by using a linear path integral along the edges, which delineates the finite volume associated with the vertex. For vertex A in Fig. 3,

$$\int_A \nabla U \mathrm{d}A = \oint_l Un \, \mathrm{d}l \qquad (2)$$

where integration along the path l in this case is equivalent to integration along the edges *ab, bc, cd, de, ef,* and *fa*. Knowing the gradient of the gasdynamic parameter in the volume related to vertex A will allow us to extrapolate the values of this parameter at any location within the volume. This permits us to evaluate the first guess for U at the edges of the dual grid. The final implementation of the second-order algorithm has been described previously.

A schematic flowchart of the basic steps of the second-order algorithm implementation is shown in Fig. 4.

Simulations of the Generic Pulsed Detonation Engine

In this section, we present sample results of simulations of the generic PDE device using the numerical code described in the preceding section. In Fig. 2a, the computational domain containing the PDE main detonation chamber is shown covered with the unstructured grid. In our sample simulation, we have chosen a small ≈ 15-cm-long and ≈ 15-cm-i.d. cylindrical chamber with a small converging nozzle. This geometry is one of a number of the geometries we have analyzed in a parametric study whose goal was to evaluate and optimize a typical PDEC device. The device shown in Fig. 1a does not represent the optimum and is given here to illustrate our methodology. We consider a situation when the PDEC serves as a main thruster for a vehicle traveling in air with the velocity of $M = 0.9$ and located at the aft end of the vehicle. The main objectives of the simulations presented here are as follows:

1) To find the maximum cycle frequency. This is determined by the time required from detonation, exhaust of combustion products, and intake of fresh charge for the next detonation.

2) To calculate the thrust produced during each cycle and the integrated thrust as a function of time.

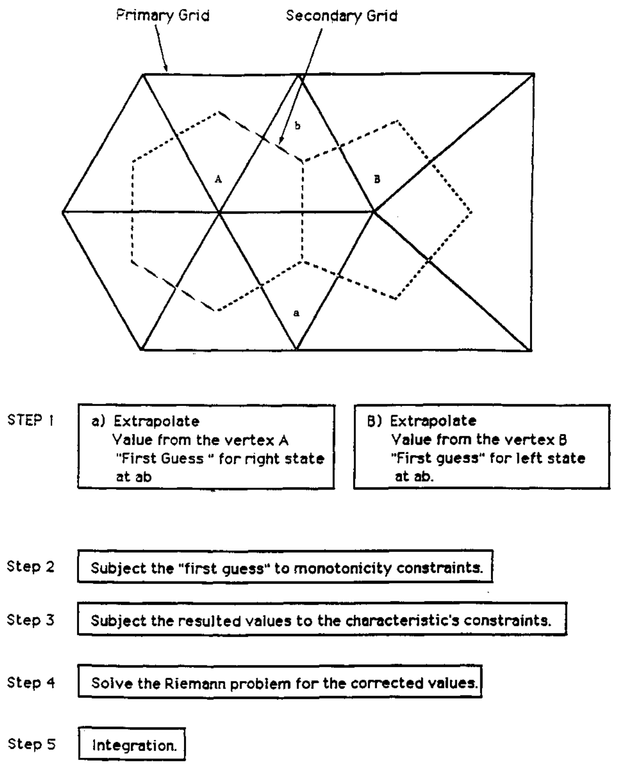


Fig. 4 Grid schematic and outline of steps for second-order Godunov method.

The simulation begins at $t = 0$ when we assume an ideal detonation process has taken place in a stochiometric propane/air mixture. Initially the detonation wave has traveled from the open aft end of the chamber toward the interior with a maximum velocity of 1800 m/s and maximum pressure of 20×10^5 Pa. The distribution of pressure, velocity, and density of the detonation wave is defined through the self-similar solution for a planar detonation wave. These distributions are shown schematically in Fig. 5. The wave was directed toward the interior of the chamber to capture the kinetic energy of the wave and to prolong exposure of the inner chamber walls to the high pressure. In Fig. 6, simulation results are shown at time $t = 0.19$ ms in the form of pressure contours and particle paths from different locations inside and outside the detonation chamber. From the pressure contour plots, we observe that the shock reflection from the inner wall has taken place and detonation products are expanding into the ambient airstream. The flow inside the chamber is choked due to the converging nozzle and the maximum pressure behind the shock is ≈ 8 atm. The pressure inside the chamber is less than 3 atm. The strong expansion of the detonation products into the ambient airstream produces a shock wave with a spherical-like front rapidly decaying in strength. As a result of the interaction of the expanding detonation products with the external flow, a large toroidal vortex is created. The vortex is carried away quickly from the chamber by the external flow and by its own flow momentum.

In Fig. 6a, we also show trajectories of the particles introduced inside the chamber and just above the nozzle. Examination of these trajectories allows us to follow the dynamics of the chamber evacuation and refill. In order to track the detonation products, we initially place marker particles inside the chamber at three cross sections in clusters of four distributed normally to the detonation chamber axis. Each particle has a different color; however, particles in the same cluster have the same shade of color. At the three chosen cross sections, we have designated shades of red, yellow, and green for the particles located correspondingly at the left end, center, and beginning of the nozzle cross sections of the chamber. The movement of these particles is shown by connecting them with a continuous line beginning with particle location at $t = 0$ to the present time. In Fig. 6a, we observe that at time $t = 0.19$ ms all particles originally in the nozzle cross section and three of the particles originally in the midsection have left the detonation chamber. However, particles originally introduced on the inner wall of the chamber have only advanced to the nozzle region.

We use a different technique for observing the motion of the ambient gas outside the chamber. Here a cluster of seven

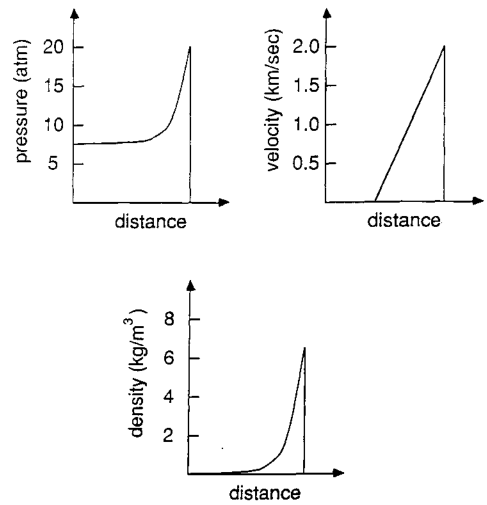
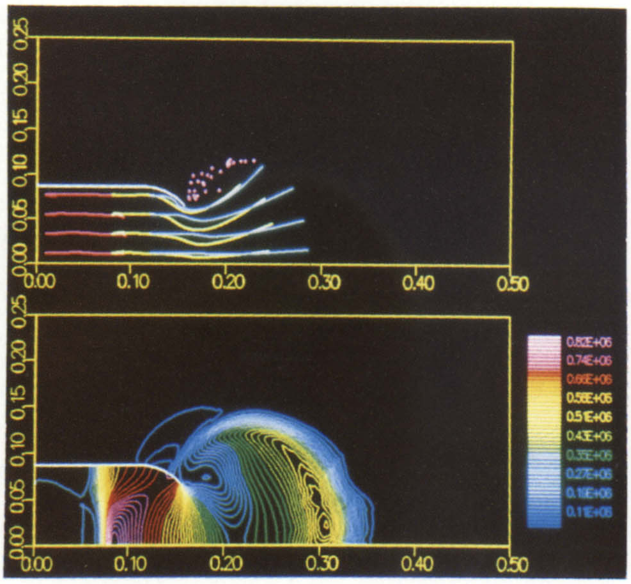
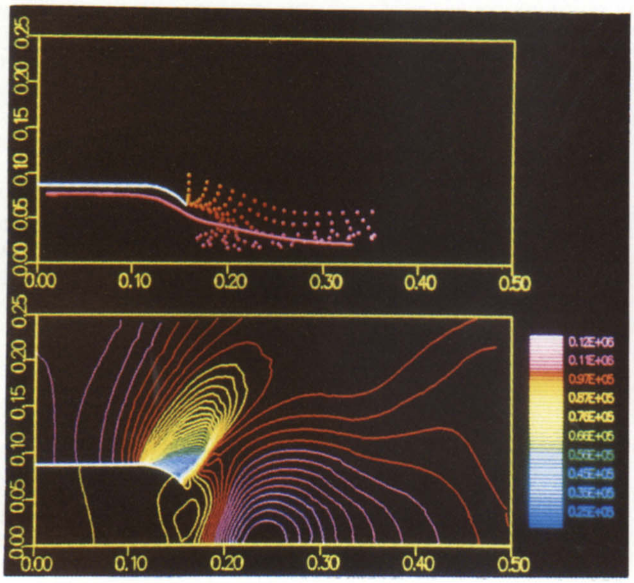


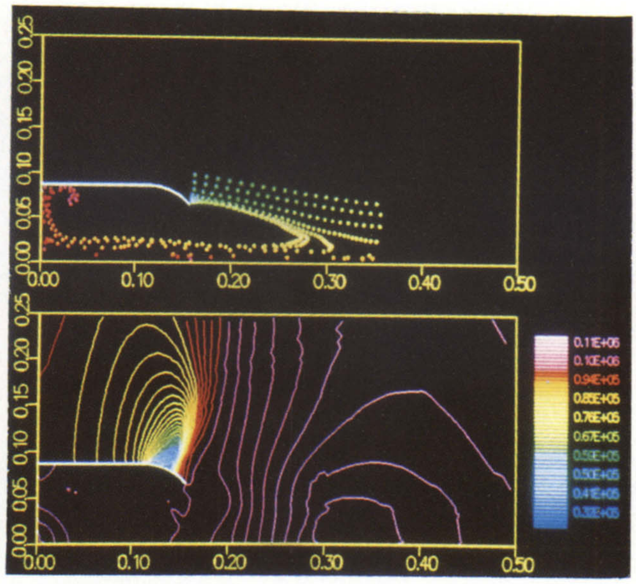
Fig. 5 Distribution of gasdynamic parameters behind the detonation wave according to a one-dimensional self-similar solution.



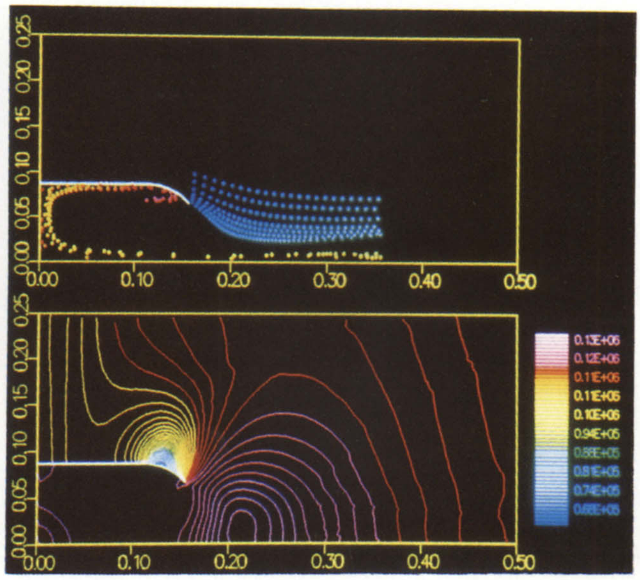
a) $t = 0.19$ msec



b) $t = 1.7$ msec



c) $t = 4.7$ msec



d) $t = 7.4$ msec, end of first detonation cycle

Fig. 6 Pressure contours and particle paths for various times during the PDEC simulation.

particles is introduced every 0.05 μs in the external flow above the nozzle. All such particles are traced as they move with the flow until they leave the computational domain. At any given time only the current location of the particle is displayed, and since the particles are introduced periodically with time there are a large number of particles to trace. We assign a color to every cluster of external particles to keep track of the time when they were introduced in the calculation. The colors vary from magenta, for those particles introduced early in calculation, to blue, for those introduced shortly before the end of a detonation cycle. In Fig. 6a, corresponding to very early times, only one cluster of external particles is visible. This cluster was introduced at $t = 0$ and is tracking the expanding flow of the detonation products.

In Fig. 6b, the simulation results are shown for $t = 1.7$ ms. The pressure contours show that a shock wave develops at the external edge of the nozzle as a result of a strong expansion of the Mach 0.9 external flow. As a result of overexpansion of the detonation products, the pressure inside the detonation chamber is lower than the ambient pressure, causing the shock to be located lower on the external surface of the nozzle. The external flow about the chamber has a stagnation point on the axis of symmetry downstream at ≈ 25 cm. At this time, it is evident from the particles' trajectories that most of the detonation products have left the chamber. Figure 6b shows one continuous trace of the particles originating at the back wall of the detonation chamber having advanced well ahead of the stagnation point in the external flow.

The marker particles released outside and just above the nozzle's exit show two distinct flow paths. One path takes the flow past the stagnation point to the right of the detonation chamber; this flow path is marked by the four upper particle traces. Another flow path is marked by three lower particle paths released close to the nozzle surface and is deflected toward the detonation chamber exit. Figure 5b shows particles marking this deflected stream approaching the detonation chamber nozzle. The magenta color of these particles indicates they were released at ≈ 0.5 ms.

Figure 6c corresponds to the simulation time $t = 4.7$ ms. The pressure inside the chamber has risen ≈ 1 atm. Higher

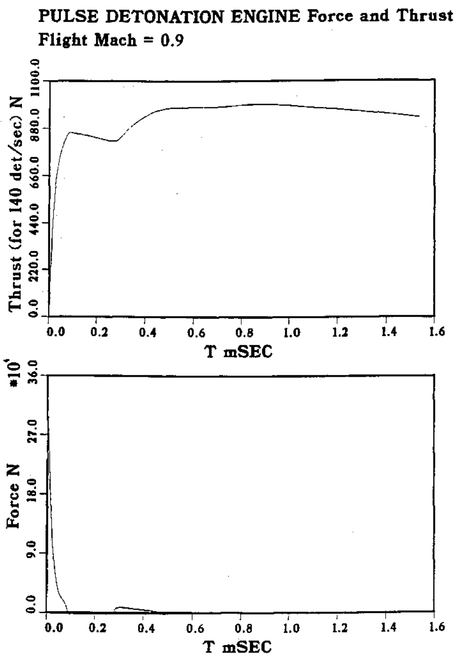


Fig. 7 Thrust and force generated by PDEC as a function of time.

pressure at the chamber exit has resulted in the shock standing on the external surface of the nozzle to move upward. The particles marking the movement of fresh air into the chamber show these to be well inside with some reflecting from the end wall giving a second stagnation point for the reversed fresh airflow.

Figure 6d corresponds to the end of the first cycle when the detonation chamber is filled with fresh charge and ready for the next detonation. In this figure, the particles' paths indicate that the chamber refills in a pattern suitable for fast mixing of the fuel-air mixture. We conjecture then that fuel injection along the chamber axis will promote fast fuel-air mixing. We can see in Fig. 6d that further injection of external air inside the chamber stopped, and from that point on the mixture composition in the chamber will be fixed.

In Fig. 7, the total force and time-averaged thrust generated by the device in the simulations discussed previously are shown as a function of time. The time-averaged thrust is based on the total time for one cycle. As seen in Fig. 7, initially a very large force of $\approx 1.5 \times 10^5$ kg is felt on the end wall of the detonation chamber. This is a result of the inwardly moving detonation wave used in our simulation. Very early during the sequence, this wave reflects from the left wall of the detonation chamber briefly generating a large force. This force rapidly decays and at $t \approx 0.1$ ms changes sign due to interaction of the strong shock wave with the converging nozzle. This effect is noticeable in the thrust data; the average thrust decreases somewhat after reaching levels of ≈ 1980 N. The shock partially reflects from the converging nozzle walls and generates a wave moving to the left wall. The reflected wave thereafter generates positive thrust from $t \approx 0.3$ ms. Finally, thrust levels reach the maximum of ≈ 2200 N and then decay slowly as a result of the cross-sectional drag force. The simulations predict that to sustain this level of thrust will require a detonation frequency of about 150 Hz. All simulations were performed on a Stellar workstation.

Conclusions

The main intent of the present study was to carry out a review of the relevant literature in the area of detonation propulsion, to assess the state of the art, and to recommend future research based on our findings. We have reviewed the literature and presented our summary in the first section of this paper. Our initial conclusion from the review is that there is a substantial body of evidence leading toward the possibility of producing propulsion engines with significant thrust levels based on an intermittent detonation.

Most of the historical attempts at producing thrust based on the intermittent detonation cycle were carried out with the same basic experimental setup; namely, a long straight detonation tube employing forced fuel injection at the closed tube end. We have discussed the many reasons why such a device cannot take proper advantage of the physical processes associated with detonation.

The experiments performed at the Naval Postgraduate School using a self-aspirating mode of operation for a pulsed detonation thruster produced very useful results which, upon further examination, provide us with a route toward practical propulsion engines of variable thrust levels that are both controllable and scalable.

We have explored some of the implications of the possible applications of the self-aspirating detonation engine concept and have developed a suitable numerical simulation code to be used as a design, analysis, and evaluation tool. In fact, the preliminary analysis of a candidate detonation chamber flow was shown to be dominated completely by unsteady gasdynamics. An attempt to understand the flow properties based on any steady-state model or one-dimensional unsteady analytical model will miss such important aspects as fuel-air mixing and shock reflection from internal geometrical obstacle such as the converging nozzle. The unsteady simulation code developed during the course of our study is a necessary tool that we plan to use in a study leading to a feasible prototype engine design realizing the full potential of the intermittent detonation process.

Acknowledgments

The work reported here was supported by the Defense Advanced Research Projects Agency under Contract N66001-88-D-0088. The authors express appreciation to Adam Drobot and Aharon Friedman for helpful suggestions and advice.

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