# A REVIEW OF RESEARCH ON PULSE DETONATION ENGINES

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## Introduction

In principle, detonations are an extremely efficient means of burning a fuel-air mixture and releasing its chemical energy content. However, detonations have been explored for propulsion applications only for the past fifty years or so because of the difficulties involved in rapidly mixing the fuel and air at high speeds, and initiating and sustaining a detonation in a controlled manner in fuel-air mixtures. Recently, there has been a renewed interest in the application of intermittent or pulsed detonations to propulsion and hence it is timely to review the past work.

In this paper, the status of experimental and theoretical research on pulse detonation engines (PDE) will be presented. First, a cycle analysis is performed to show that the efficiency of a detonation cycle is close to that of the constant-volume cycle which is much more efficient than the constant-pressure cycle, characteristic of most conventional propulsion systems. Other advantages of detonations will also be discussed. Then a review of the early attempts to use detonations for propulsion is presented. After a brief discussion of the possible reasons for the successes and failures of the early attempts, more recent work in the past decade on PDE are reviewed. Observations from the lessons learnt in the past and their potential implications for further development of PDE are also presented.

## Why Detonations?

As mentioned before, very rapid material and energy conversion is a key feature of detonations. This rapid "burning" or material conversion rate, typically tens of thousands of times faster than in a flame, can lead to several advantages for propulsion such as more compact and efficient systems. Because of the rapidity of the process, there is not enough time for pressure equilibration and the overall process is thermodynamically closer to a constant volume process than the constant pressure process typical of conventional propulsion systems. To illustrate this point, three idealized thermodynamic cycles (constant pressure, constant volume and detonation) are compared in Fig. 1. Since all process except for heat addition have been maintained the same, the work done or relative thermodynamic efficiency of the three combustion processes can be obtained by comparing the three enclosed areas. For the efficiency, the work output is divided by the heat input which was set to be the same for the three cycles. The thermodynamic efficiencies for the three cycles are: 27% for constant pressure, 47% for constant volume and 49% for detonation. From the figure and the above numbers we see that the thermodynamic efficiency of the detonation cycle is close to that of the constant volume cycle. The process itself is different with a decrease in specific volume and a significantly higher pressure being attained during detonations. Several other advantages have been stated for using pulsed detonations in propulsion devices and these will be discussed in the full paper.

## Early Research

The development of the concept of Pulse Detonation Engines (PDE) has been traced back to the pioneering work of Hoffmann [1] in a number of papers. Both gaseous (acetylene) and liquid (benzene) hydrocarbon fuels were employed with oxygen and intermittent detonation appears to have been achieved but attempts to determine an optimum cycle frequency were less successful. Nicholls et al. [2] were also exploring the concept of intermittent (or pulse) detonation waves for propulsion applications. Both single cycle and multi-cycle operations with hydrogen and acetylene as fuels and oxygen and air as oxidizers were demonstrated. The basic set up was a simple detonation tube, open at one end with co-annular fuel and oxidizer injection at the closed end. Thrust, fuel flow, air flow, and temperature measurements were made over a range of operating conditions. When the spark plug was located 2 or 5 inches from the end of the mixing plane, spasmodic firing was observed suggesting problems with fuel-air mixing. However, with the spark plug located 10 inches downstream, periodic detonations for a range of mixtures were reported. For a hydrogen-air mixture, a specific impulse of 2100 seconds was attained along with a cycle frequency of 35 Hz. They also presented a very simplified theoretical analysis that gave overall results very much in agreement with their experimental data on hydrogen but less so in the case of acetylene. The agreement was partly fortuitous since the measured thrust-time history was significantly different from the theoretical. Recently, questions have also been raised whether the periodic waves observed in this early work was actually detonations or some form of high speed deflagrations. It is interesting to note that they also attempted initiation from the open end but were not successful. The issue of open end or closed end initiation continues to be a point of contention to this day. A set up similar to that of Nicholls [2] was constructed by Krzycki [3], who used automotive spark plugs for ignition. He demonstrated operation at 60

Hz with propane-air mixtures but there is some doubt whether the device was operating in the detonative mode or merely as a pulse jet engine due to the low initiation energies employed. His overall conclusion was that although thrust was possible from such a device, practical applications were not promising.

## Research in the 1980's and Early 90's

In the late 80's, the concept of using intermittent or pulse detonations was re-examined experimentally [4]. An ethylene-oxygen detonation in a small diameter tube was used as a pre-detonator to initiate detonations in a larger tube containing an ethylene-air mixture. Periodic fuel injection within the naturally aspirated tube resulted in an intermittent frequency of 25 Hz. Specific impulse estimated using the pressure time history and the amount of fuel consumed ranged from 1000 to 1400 s. The velocity of the observed waves (less than 1 km/s) are significantly below the C-J detonation velocities for the reported mixtures, indicating that a fully developed detonation wave was not formed.

Soon, quasi one-dimensional numerical simulations were carried out to investigate the ideal performance of a PDE burning a stoichiometric mixture of hydrogen and air [5]. The system simulated consisted of a 50 cm long main tube attached to a 43 cm long diverging nozzle. Issues of mixing, ignition and transition to detonation were all ignored. Overall performance calculated by integrating the instantaneous thrust and the fuel flow rates gave a specific impulse of about 6500 s and a potential operating frequency of 667 Hz. The first look at the interactions between the flow inside the chamber and that outside appears to be the work of Eidelman et al. [6,7], who simulated a cylindrical detonation chamber with air inlets. In their two-dimensional simulations, planar detonation was assumed to be created at the open end and traveled towards the closed end, ejecting some of the burnt gases through the open inlets. In this configuration, the system can operate in a self-aspirating mode. Thrust was predicted to scale linearly with detonation chamber volume and operating frequency.

Many of the early efforts on intermittent or pulsed detonation engines have been reviewed in Ref. 7 and 8, where a link is also made between these detonation engines and pulse jet engines (which do not use detonative combustion). In addition, Ref. 8 provides a detailed summary of the numerical investigations of a generic PDE device. A characteristic feature of this device is that detonation is initiated at the open end and travels towards a thrust wall at the closed end. An advantage of this approach is that it is self-aspirating. Air is entrained into the chamber through inlets near the closed end when the pressure falls below atmospheric during part of the cycle. Unsteady Euler simulations were used to study the operation of the device from static (M = 0) to supersonic (M = 2) conditions. As stated in their paper, a proof of principle experimental demonstration of the PDE mode of operation where detonation is initiated at the open end still needed to be done.

Bussing and Pappas [9] provided a detailed description of the basic operation of an idealized PDE. They also reported some one-dimensional studies of PDE's burning hydrogen-oxygen and hydrogen-air mixtures. The detonation was initiated at the closed end in this engine using a high temperature and high pressure region. An advantage of this design is the confinement provided at the closed end which should enable a more rapid initiation and establishment of a detonation. Both air-breathing and rocket mode of operation of this design were discussed. Lynch et al [10] presented a computational study of an axisymmetric PDE with a straight inlet, very similar to that of Eidelman et al. [6,7]. Various inlet lengths from 1 to 12 cm and flight Mach numbers of 0.8 and 2.0 were studied. The results were similar to those reported earlier except that some additional details of the detonation front were resolved in these studies.

## More Recent Research

In the past few years, there have been an explosion of papers related to the PDE and complete sessions have been devoted to the topic at the annual AIAA/ASME/SAE/ASEE Joint Propulsion Conferences. Due to space considerations, only selected papers from these years are briefly discussed here. Sterling et al. [11] conducted one-dimensional numerical investigations of a self-aspirating PDE. A key observation from their studies was that only a portion of the detonation tube can be filled with fresh charge under self-aspirating operation. In spite of this limitation, they reported a specific impulse of 5151 seconds for a hydrogen-air system. However, they concluded that the ideal performance of such an engine is "near those of other hydrogen-fueled/air breathing engines".

Several basic shock tube experiments related to the development of a hydrogen-fueled PDE was described by Hinkey et al. [12]. These include the measurement of detonation velocities and DDT (deflagration to detonation) transition lengths for a range of equivalence ratios. As expected, the DDT lengths were found to be too large for practical applications even in hydrogen-oxygen mixtures. Therefore, traditional techniques such as the use of a Schelkin spiral were tried to reduce the transition length. A factor of 2 to 4 reduction was observed over the range of equivalence ratios investigated. This work highlights the difficulties involved in obtaining a fully-developed detonation in a short distance (as assumed in the conceptual studies and numerical simulations discussed above) and questions if the detonations reported in previous experimental investigations [2-4] were really fully transitioned from deflagrations. An interesting PDE concept presented by Bussing [13] was that of a rotary valved multiple-pulse detonation engine. Here, several detonation chambers are coupled to an air inlet and fuel source using a rotary valve as suggested in one of the early papers of Nichols [2]. The rotary valves allow the filling of some detonation chambers while others are detonating or exhausting.

The importance of adequately mixing the fuel and oxidizer was highlighted by the experimental investigations of Stanley et al. [14] who obtained very low sub CJ velocities when injecting the fuel and oxidizer at different times and not taking extra efforts to 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. This study also showed that raising the initial pressure was beneficial. The computational studies of Eidelman showed that the PDE engine could operate even for a range of transitional detonation regimes, that produced nonplanar or non fully developed detonations [15]. Aarnio et al. [16] discussed two failure modes: DDT transition failure and premature ignition. In both cases, the system continued to operate, though there would be loss of thrust. In that paper, detailed discussions of the pressure and thrust histories during a 5 Hz, 20 cycle operation was also provided..

A conceptual design of a multi-tube PDE with a single air inlet duct was discussed by Pegg et al. [17]. Time dependent CFD analysis indicated that the inlet isolater/diffuser concept would work and did not allow enough time for the formation of destabilizing hammershocks. Performance analysis including component efficiencies reported in the paper indicate that operational frequencies of the order of 75 to 100 Hz are required for the Mach 1.2-3 flights considered. At the same meeting (32nd JPC), experimental data indicating multicycle operation at 100 Hz with a rich ethylene-oxygen mixture was presented by Sterling et al. [18]. DDT enhancement devices and predetonators were used in the experiments. In spite of this, detonations did not occur all the time and when detonations failed the tube became very hot and testing was suspended. Hence the maximum testing time was reported to be 0.5 seconds. In spite of this limitation, the two works [17 and 18] taken together highlight the possibility of PDEs burning hydrocarbon fuels for realistic missions.

Five different nozzle shapes and their effect on performance were studied computationally by Cambier and Tegner [19]. Their results indicate that the presence of a nozzle can affect the performance of the PDE by increasing the thrust delivery during the ignition phase. The bell-shaped nozzles appeared to give higher performance than shapes with positive curvature. Their results also showed that nozzles also affected the flow dynamics and hence the timing of the various phases of the engine cycle. More recently [20], the effect of various nozzle shapes, including converging, diverging and straight have been re-examined computationally. The converging sections of nozzles introduced shock wave reflections while diverging sections generated a negative thrust for a portion of the cycle due to overexpansion. In spite of these limitations, the overall conclusion of these studies was that "nozzles can drastically increase efficiency of the PDEs". However, factors such as the effect of the nozzles on cycle frequency and the detailed structure of the flow have not been elucidated. This appears to be an area that needs further investigation.

Other recent efforts have focused on demonstrating the operation of single and multitube combustors coupled to an inlet using a rotary valve mechanism [21]. The valve serves to both meter the air flow into the combustor and to isolate the inlet from the high pressures produced during the detonation cycle. Utilizing multiple combustors which 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 use of PDEs for rockets has been revived recently [22]. The rocket mode of operation is very similar to the air-breathing engine with ignition at the closed end, except that the oxidizer also needs to be injected into the system periodically. An advantage of PDEs for rockets would be their higher power density, thus enabling the development of more compact rockets. The paper shows the pressure traces from a pulse detonation rocket engine operating at 145 Hz on a hydrogen-oxygen mixture.

More recently, a two tube rotary valved PDE with flight-size components was operated at 40 Hz per combustor for 30 seconds with an ethylene-air mixture [23]. In addition, throttling of the device allowed operation at three thrust levels during a 10 second demonstration experiment. Contrary to some earlier estimates, the thermal loads were significant and it was not possible to operate for more than 3 seconds without water cooling. It is not clear if this was because of periodic detonation failures and consequent deflagrative modes of combustion as reported in some earlier studies.

The work reported in the open literature and discussed above has focused on gaseous fuels. However, for volume-limited propulsion applications, PDEs operating on liquid fuels need to be demonstrated. In a recent study, Brophy et al. [24] reported on experiments using JP-10/oxygen and JP-10/air aerosols. The fuel-oxygen mixture was successfully detonated to obtain an engine operating at 5 Hz but the tests with the fuel-air mixture were not successful.

Computational studies have also made progress [20,25,26]. The effect of nozzle shapes and incomplete transition to CJ detonations have been studied by Eidelman and Yang [20]. They find that the cycle efficiency will be virtually the same whether a CJ detonation is initiated instantaneously or if it attains the CJ value only at the end of the detonation chamber. Primarily based on this, they come to an interesting conclusion that "initiation energies that are required for PDE operations can be small and comparable with energies required for initiation of (other) combustion process." However, this is yet to be substantiated experimentally. Injection and mixing issues that have generally been ignored in previous numerical studies are also beginning to be addressed [25,26].

## Concluding Remarks

As briefly reviewed above, pulsed detonations have been explored extensively for propulsion applications because of their inherent theoretical advantage over deflagrative combustion. The basic ideas behind most of the current systems being investigated have been known and discussed for many decades. Furthermore, developments to date have focused on idealized systems or laboratory-scale devices operating on gaseous fuel-oxygen mixtures. However, advances in computations and experimental diagnostics appear to be poised to make practical pulsed detonation engines burning liquid fuels in air a reality.

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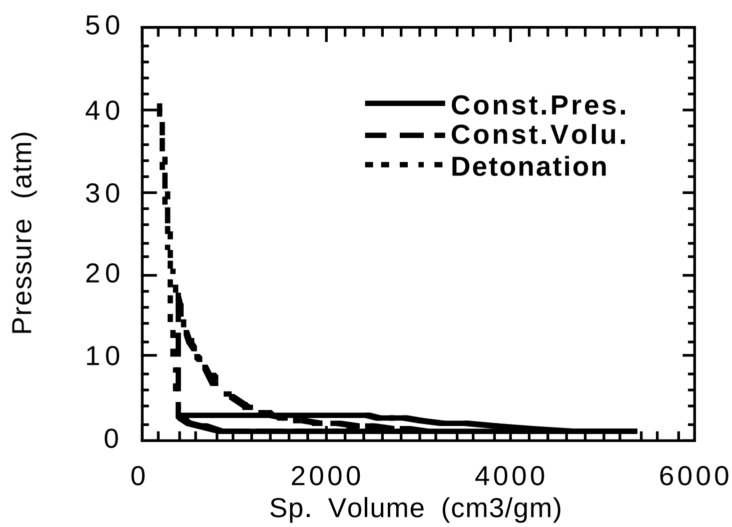


Fig. 1 Comparison of idealized thermodynamic cycles for constant pressure, constant volume and detonation modes of combustion.