A Characterized Status Report on Pulse Detonation Engine

Bharat Ankur DOGRA*, [1], Mehakveer SINGH[1], T. K. JINDAL[1]

*Corresponding author
[1]Aerospace Engineering Department, Punjab Engineering College,
(Deemed to be University),
Sector-12, Chandigarh, 160012- India,
mechanicalerankur906@gmail.com*, mehakveersingh11@gmail.com,
tkjindal@pec.ac.in

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Abstract: *Pulse Detonation Engine (PDE), is an exciting propulsion technology for the future and has been able to seek considerable attention over the last era. It has the potential to work efficiently in the modern cosmos. It works on a Humphrey cycle offering a great opportunity, which outweighs the conventional Brayton cycle. The operating cycle of PDE starts with the fuel-oxidizer mixture, combustion and DDT followed by purging. The PDE combustion process, which is a unique process, leads to consistent and repeatable detonation waves. This pulsed detonation combustion process causes rapid burning of the fuel-oxidizer mixture, which cannot be seen in any other combustion process as it is a thousand times faster than any other mode of combustion. PDE not only holds the capability of running effectively up to Mach 5 but it also changes the technicalities in space propulsion. The present study deals with the categorization of design approach, thermal analysis, performance analysis, fuel-based analysis, PDE combustors, detonation propagation, experimentation analysis, valving techniques, ignition studies, parameters & specification optimization, instrumentation, thrusters, parameters affecting specific impulse & thrust, hybrid PDE's & turbine integration.*

Key Words: *Pulse Detonation Engine (PDE), Deflagration to Detonation Transition (DDT), Rotating Detonation Engine (RDE), specific impulse, Shchelkin spiral, Rotating Detonation Wave Engine (RDWE).*

1. INTRODUCTION

With the advent of propulsion technology, a name that came into the picture was- an Air-breathing engine. These engines were sub-categorized according to the type of combustion process engaged. Now, the propulsion systems may be further indexed based on the deflagrative or detonative mode of the combustion utilized. As we go in the past, we find that the first powered flight was accomplished by Wright Brothers in late 1903, on an aircraft driven by a reciprocating internal combustion engine in the field of propulsion; the first turbojet-powered aircraft, HE178, was flown by German Hienkel Company in 1939. Since then the gas turbine engines have become the workhorse of the aircraft industries, ships, tanks & electric power plants [1]. After that, piston engines were used to power small propelled aircraft. However, helicopters and other large propeller aircraft are powered by turboshaft & turboprop engines but these two engines are limited to subsonic speed range as propeller gets noisy and hard to maintain the propulsive power over 550km/h. Mach number range of Gas turbine engines ranges from 0 to 3.5 for turbojets. Beyond the Mach range of 3.5 comes ramjet which is more effective up to this range and not beyond Mach 6. Scramjets are used for combustion at supersonic speeds. Unfortunately, both ramjet and scramjet engines need some starting velocities i.e. 0.8 Mach and 5-6 Mach. The only engine left with a wide range of speed is the rocket engine. But due to low specific impulse, as it carries onboard oxidizer storage, these cannot be reused for further flights. It has been six decades since the advent of gas turbine engines after which there has not been a major revolution in engine technology, which could replace the gas turbine engine, and thereby delivering better performance in terms of thrust, fuel efficiency, cost and range of Mach number of operations. Only the pulsed detonation engine (PDE) has the capacity to offer all the above and more. The PDE is an internal combustion reaction engine that works in a pulsed cyclic fashion utilizing a constant volume combustion process; this makes it somewhat similar to pulsejet engine which uses deflagrative combustion and has traditionally only been used for subsonic applications. PDE's on the other hand, use cyclic detonation waves and can theoretically operate up to about Mach 8, although at hypersonic velocities, the continuous detonation wave engines are more effective. The basic working principle of PDE follows filling of the fuel-oxidizer mixture, ignition, combustion, wave formation followed by purging of pollutants. Nowadays, PDE is in research trend. Researchers from all over the world have moved to these propulsive technologies. They have much interest in the historical background of PDE, thermodynamics analysis, detonation initiation, and deflagration to detonation devices or mainly the wave transition devices as their main subject in detonation combustion research area. Many countries are involved in these research areas of which we mention: United States, Russia, Japan and China, Germany and Malaysia. There is a significant increase in the number of publications in this area of research after the first PDE powered flight in 2008 [2]. In detonation, combustion takes place after ignition of fuel-air mixture which is then followed by a wave called the shockwave. This shockwave followed by combustion wave is the center of attraction for the researchers [3]. Pratt and Whitney began to develop the pulse detonation engine in 1993. Their research approach was to study the deflagration to detonation transition through the pulse detonation engine. The feasibility study of a reaction device operating on intermittent gaseous detonation wave is considered by Nicholls et al [4]. They conducted a study to investigate the thrust, fuel flow, air flow, and temperature over the range of operating conditions. Recently, many countries give much importance to the research of multimode combined detonation engine in hypersonic aircrafts propulsion system [5]. Kailasanath [6] gave a complete review on practical implementation on pulse detonation engine. He also studied the deflagration to detonation transition in obstacle geometry. The detonation combustion parameters such as Chapman velocity and pressure are well derived in this study. Wilson and Lu [7] summarized the studies for PDE based propulsion system. They focused detonation waves to hypersonic flow simulation and power generation. Smirnov et al. [8] studied numerical simulation of the detonation engine fed by the fuel-oxygen mixture. The advantage of a constant volume combustion cycle as compared to constant pressure combustion was in terms of thermodynamic efficiency focused for advanced propulsion on detonation engine. The next part of this paper gives a brief insight of the various studies and investigations done and found by various researchers in the past as well as in recent times. A report on PDE research has been fully categorized and put into form in the remaining part of the study and research done in the Punjab Engineering College (PEC), Pulse Detonation Engine (PDE) Lab of Aerospace Engineering Department.

2. REVIEW ON VARIOUS DESIGN APPROACHES OF PDE

J David Carter et al. [1]. Experiment on 4-inch diameter detonation engine requires improvement in fabrication, installation, and actual testing on large PDE. By analyzing, the engine developed a peak thrust of 1 Knot and also revealed a sub-C – J (Chapman – Jouguet) [9] pressure wave with a velocity of 1288 to 1530m/s, which can be sustainable for the length of the 1 m tube. It has also been found that the use of multiple lower energy spark plug in circumferential placement has solved the problem of short life spans of the spark plug. **William Stoddard et al.** [2]. By using shockwaves carried through crossover tubes of varying lengths, bend angles and various reflective obstacles at the exit of the crossover tube investigate the ignition of pulse detonation engine. The result has shown that a transferred shock wave reflecting off the wall of the driven PDE can achieve direct initiation of detonation. The result has also yielded cases where the initial shockwave reflection does not directly initiate detonation in the driven PDE but rather causes ignition leading to likely accelerated deflagration to detonation transition. Overall results have shown that there is a specific length range in which direct detonation initiation is possible for specific tube and obstacle geometries. **Louis A. Camardo II et al.** [10] In their research paper they report on three main objectives. The first objective is to remove the nozzle from Nielsen's single tube configuration and repeat similar test conditions. As a continuous branching PDE would actually fill multiple tubes; this paper also looks at the more practical case of filling the crossover duct by means of two tubes with a hydrogen-air mixture as well as with an ethylene-air mixture, neither two-tube test having the benefit of a nozzle on the tail end of the detonation tubes. The second objective is to exploit the potential of the "D" geometry as shown in Figure 1. Crossover duct showing "D" geometry and flow direction by testing it with varied crossover widths in search of an optimal width.

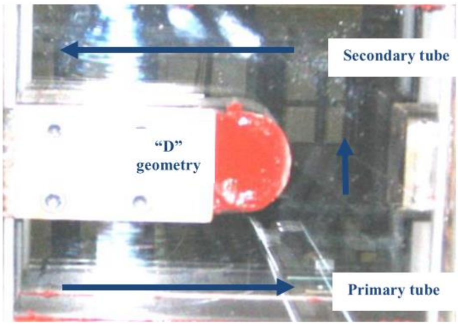

Figure 1. Crossover duct showing "D" geometry and flow direction

The final objective is to address the negative effect on the equivalence ratio due to entrainment of ambient air in the crossover duct by varying the location of the crossover from a tail-tail location to a new location in the center of the detonation tube. This location will be referred to as a mid-mid tube-to-tube detonation initiation.

Robert Driscoll et al. [3] at the University of Cincinnati carried out experiments on a Multi-Pulse Detonation Engine (PDE) crossover system. They connected the detonation tubes of varying lengths that allows a shockwave to crossover from one PDE to another. This arrangement was done to understand the effects of such connections on the driven PDE. They then studied the increased functionality in the PDE crossover system. Their study aimed to investigate the effect of crossover tube entrance locations on the operability of a driven PDE. **William A. Stoddard et al.** [11]. A study has been done on the potential to ignite a detonation by reflected shock in a Pulse Detonation Engine (PDE) from another PDE over a wider range of crossover tube lengths with dual crossover tubes carrying the shock generated by a detonation. The frequency of firing was also varied to test viability at high frequencies and the dependence of detonation on frequency. Two main configurations of 2-crossover-tube PDE configurations were tested. One configuration was with parallel tubes, one downstream of the other. The other consisted of the same driver PDE configuration, but with a modified fitting allowing the two to converge at a single spot at the second PDE.

3. THERMAL ANALYSIS OF PDE

Nicholas C Longo et al. [12] conducted an experiment on PDE driven radial turbine to measure the exhaust parameters made for pulse detonation engine with or without a turbocharger. The change in energy of the working fluid temperature at 10Hz without the turbocharger is 2058K and with the turbocharger 1839K; a total of 2.82KW or 3.79HP should be produced by the turbocharger.

Chris A. Stevens et al. [13]. Pulse detonation engine performance was measured while operating on the endothermic products of the catalyst to minimize the energy absorbed by the fuel and caused no change in the levels of deposit formation. As well as the catalyst it caused a reduction in the heat transfer from the PDE to the fuel forcing higher operating temperature for the same level of heat addition. There are numerous advantages of using JP-7 in terms of total detonable species production and PAH (polyaromatic hydrocarbons) concentration.

R. Vutthivithayarak et al. [14] examined three thermodynamics cycles Humphrey, Fickett-Jacobs and Zel’dovich-von Neumann-Doring for detonation-based engine analysis. As a result, an inclusion of pre-compression revealed that the efficiency decreases with compressor pressure ratio. By considering a generic heat addition process, it was found that an energetic material with higher heat release yields an increased thermodynamic efficiency.

Brent A. Rankin et al. [15] proposed experimental and numerical methods for estimating temperature of exhaust plumes from a turbine driven by PDE. For this purpose, they experimentally developed an arrangement for measuring the radiation intensity of unsteady exhaust plumes exiting from the turbine driven by pulsed detonation combustion which is shown in Figure 22. The effects of operating frequency, equivalence ratio, fuel /air fill fractions, and air purge fractions on the temperatures are quantified.

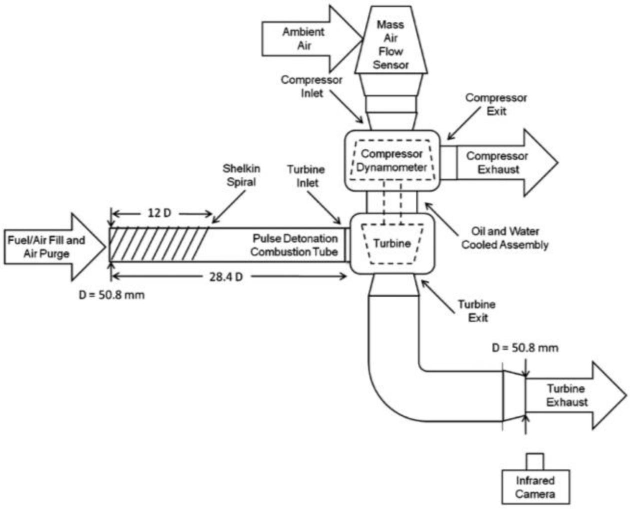

Figure 2. Schematic of experimental arrangement for measuring the radiation intensity of unsteady exhaust plumes exiting from the turbine driven by pulsed detonation combustion [15]

The results demonstrate that calibrated high-speed imaging of the radiation intensity from hot carbon dioxide coupled with inverse radiation analysis is an effective nonintrusive technique for estimating gas temperatures in low-luminosity, unsteady high-speed flows such as the exhaust plumes exiting from the turbine (see Figure 2) driven by pulsed detonation combustion.

4. PERFORMANCE ANALYSIS

Eric M. Braun et al. [16] conducted a study on the comparison of detonation engine using first and second law. In terms of specific impulse and thrust, the PDE performance was better at low supersonic range because the losses from Rotating Detonation Wave Engine (RDWE) area expansion are comparatively large. Sustainability of the detonation wave is a current problem in RDWE, but the RDWE could benefit from less complex in mixing of the exhaust and high energy density.

Dibesh D. Joshi et. al. [17] used a simulator to study the unsteady thrust characteristics. They experimentally studied the natural vibration frequencies and steadiness of simulator's operation. They concluded that after using the simulator at 5 to 20Hz and there was no resonance. The effective mass of the system was calculated by their developed technique for the cyclic loads. The actual thrust was calculated by a general approach discussed in their research paper.

According to them, the impulse transfer function of the system was to be determined to reconstruct the thrust signal from the measured input. The cyclic load was then subtracted to get the actual thrust.

They calculated the cyclic loads by multiplying the effective mass and the measured acceleration during each run. Some of the measured results are shown in Figure 3. Measured and filtered acceleration for vibrational frequencies at 5 Hz & 20 Hz respectively [17].

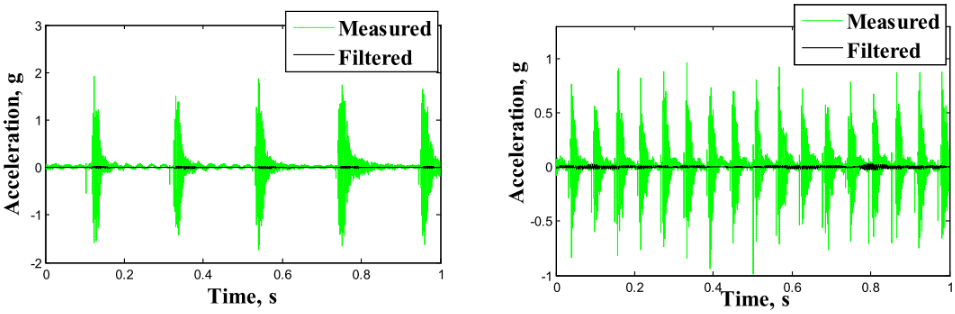

Figure 3. Measured and filtered acceleration for vibrational frequencies at 5 Hz & 20 Hz respectively [17]

They concluded that the measured acceleration was very low and hence there was no significant difference reconstructed and the compensated thrust.

Dibesh D. Joshi et al. [18]. A new approach to thrust measurement for pulse detonation engines (PDEs) to account for the effects of system dynamics. They developed a PDE to study this unsteady thrust characteristics. In their study they showed that actual thrust generated in the PDE was affected by pulse-to-pulse interaction in a fast operating PDE, interference due to propagating and reflecting stress waves initiated by detonation waves and inertial forces due to oscillation of the PDE test-rig. Finally, the compensated thrust values were used to determine the impulse which was expressed as a specific impulse as well. They had observed that the experimentally compensated impulse values were found to be 8% lower than the measured one.

Raheem T. Bello et al. [19]. The wave processes in a cycle of the pulse detonation engine are investigate on its performance during operation in the fully and partially-filled mode. The fully-filled PDE produces a simple wave diagram characterized by a detonation wave, Taylor rarefaction, and exhausting rarefaction.

The partially-filled PDE produces a complex wave pattern that includes the detonation wave, Taylor rarefaction, incident shockwave, incident rarefaction, contact surface, exhausting rarefaction and several rarefaction reflections. **J. A. Roux.** [20]. The performance parameters for the ideal PDE have been presented in terms of convenient parametric algebraic equations. It was found that these expressions lead to a simple but direct comparison with other ideal parametric cycle descriptions, such as the ideal turbojet engine and ideal ramjet engine. The results showed the specific thrust performance of the ideal PDE to be superior to that of the ideal turbojet and ideal ramjet engines.

5. FUEL BASED ANALYSIS ON PDE

Takashi Shimada et al. [21] conducted a study on detonation characteristics using bio-fuel ethanol/air; they are simulated in order to be compared with JP10. Ethanol/ air detonation has small cell size to apply for PDE better than JP10 detonation and the ethanol reaction model is reasonably good when its velocity is compared with that of the experiment (Smeets 1985). The ethanol/ air two-phase detonation structure has a wide and strong transverse detonation front which clearly propagates transverse direction.

Masashi Wakita et al. [22] conducted an experiment to reduce driver gas usage of a pulse detonation engine operation by combining the reflecting board method and the driver gas overfilling method. As a result, the transition from an expanding cylindrical detonation wave to an imploding toroidal one becomes possible with a characteristic overfilling distance as small as 17.2mm. The mixing effect completely prevents re-initiation position of the toroidal detonation wave. **S. M. Frolov** [23] experimentally studied the feasibility of controlled repeatable deflagration-to-detonation transition within a length of ∼3.5m and further detonation propagation at an average velocity above 1600–1700m⁄s in a 150mm diameter. On the basis of experimental studies, Frolov had designed and tested a model of a pulsed-detonation combustor, and a prototype of industrial burners of a new generation, which produces a combined shock wave (mechanical) and thermal effect on objects blown on with combustion products. Frolov measured the Steady-state temperatures of structural elements of the PDC in the course of long-duration testing in a pulse-detonation mode with a frequency of about 2Hz without forced cooling. His results showed that the forced cooling is generally required only in the parts of the burner duct traversed by the detonation wave. According to him the PDC operation frequency and thermal power can be increased by increasing the supply pressure of air and natural gas. Furthermore, the thermal power can be increased by applying multi-tube PDC configurations.

6. PDE COMBUSTORS

Kumad Ajmani et al. [24]. A research on chemical components to reduce the kinetic mechanism and successfully obtain the agreement for the location for detonation initiation and C – J (Chapman-Jouguet) velocity of the detonation. In result, a new method for jet-A had been investigate for combustor design application where equilibrium temperature is approximately close to operating temperature.

Fuhua Ma et al. [25]. They conducted a study on the pulse detonation combustor for pulse detonation turbine engine application. The effect of key sizing and timing parameters, including PDC length, nozzle area ratio, operation frequency, valve open time ratio, and fuel fil time ratio, were investigated systematically.

Moreover, total pressure ratio across the PDC optimizes by using hierarchical strategy. The results showed that the maximum pressure ratio obtained is approximately 18 percent higher than an initial baseline case.

Timothy Ombrello et al. [26]. To enhance mixing in pulse detonation combustor applied to a supersonic flow, the initial detonation wave from the PDC produce a large bow and barrel shock structure from the highly under-expanded jet whose plume grows to more than 7.5cm in diameter at a location of 12.7cm downstream.

Overall, the experimental and numerical results have provided the first look into the dynamics involved in the transient behavior of a PDC exhausting into a high-speed flow. **Matthew L. Fotia et al.** [27].

7. DETONATION PROPAGATION, EXPERIMENTATION & ANALYSIS

Robert T. Fievisohn et al. [28]. They optimized geometries for pre-detonators in the pulse detonation engine to successfully transition of detonation in the main detonation tube. This experiment showed that transition depends on the location where expansion occurred with respect to the structure of the detonation wave.

Jeffrey M. Nielsen1 et al. [29]. They made an experiment on detonation propagation through duct in PDE in which velocity at, or above the upper C – J (Chapman-Jouguet) velocity point is desired and considered successful detonation.

It was found that the delay in spark plug put greater impact in wave speed. The “U” shape geometry turns the flow, creates the great reflection and a width at least 75% of the initiated tube provided the best condition for direct initiation.

James Karnesky et al. [30] Their study aims to measure the engine performance of a PDE under choked flame conditions. When a combustible mixture in a pulsed detonation engine fails to undergo transition to detonation, the combustion wave consists of turbulent flame which eventually accelerates to a steady state supersonic velocity, referred to as the choked flame velocity.

Robert Driscoll et al. [3]. They deal with the effect of sustainability of an annular array of shock-initiated detonation tubes connected in tandem. Number of parameters were studied to achieve the sustainability array. It was investigated that the PDE length were depend on DDT run length in the driven PDE.

David Munday et al. [31]. They present a new six tube air-breathing PDE mated to an axial-flow power turbine with each PDE tube supplying one-sixth portion of the turbine with close coupling to enable study of the turbine performance under both pulling flow and partial conditions.

Figure 4 shows the time traces from two ionization sensors placed four inches apart in a single 2-inch PDE tube.

The sudden drop in signal indicates a sudden reduction in resistance between the probe’s electrodes revealing the arrival of ionized gas at the probe’s location. The time difference between the signal drops of the two probes is 228μs.

This gives a wave speed of 1782m/s which compares reasonably well to the predicted C – J (Chapman-Jouguet) speed of 1850m/s for this mixture.

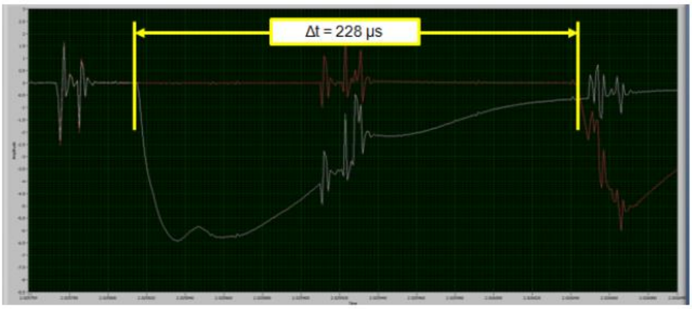

Figure 4. Wave traces after DDT from a pair of ports separated by four inches [31]

Robert Driscollet et al. [32]. This is a study on the propagation of a shock wave through a crossover tube. As a result, the initiation performance in the driven detonation tube declined when the incident shock strength decreased below Ms=2.0. A bend to the end of the crossover tube increased the driven detonation tube initiation performance by enhancing the strength of the transferred planar shock wave by an average of 20%. Furthermore, the experiment showed that a 45-degree bend located at the exit of the crossover tube increased the success rate in the driven PDE when compared to other bend configuration. **Dibesh D. Joshi et al.** [33]. A new method was developed to determine the mass flow rate of propellant injected into the PDE. The method utilized the mass flow parameter of the gas used to estimate the ideal mass flow rate. The calculated mass flow rates and valve open time duration were used to calculate the total mass of propellants injected per pulse. The ideal mass flow rate calculation incorporated determination of the time varying the injection surface area, supply pressure and temperature, specific heat ratios of the gas and Mach number. **Robert Driscoll et al.** [34]. The effect of shock-initiated combustion within an air-breathing PDE. A PDE-crossover system increases the system efficiency through decreased deflagration-to-detonation transition (DDT) time while employing a single spark source to initiate a multi-PDE system. For all Reynolds number flows and equivalence ratios, shock-initiated combustion fails to initiation detonation without a DDT device. However, unassisted shock-initiation combustion increases the flame front velocity up to 16.7% for a stoichiometric mixture. With the implementation of the spiral, a decrease in DDT run-up length of up to 59.1% is measured. However, neither method was able to initiate a detonation in the test section. A single pre-detonator would be necessary to initiate the first PDE of a continuously operating system. **Robert Driscoll et al.** [35]. The driven pulse detonation engine develops from shock-initiated combustion, as strong shock wave reflection can cause ignition within a reactive mixture. A pulse detonation engine–crossover system can decrease deflagration-to detonation transition length while employing a single spark source to initiate a system consisting of multiple detonation engines. Visualization of a shock wave propagating through a clear channel reveals a complex shock train behind the leading shock wave. The shock wave Mach number and decay rate remain constant for varying crossover tube geometries and operational frequencies. However, small-diameter crossover tubes prevent these auto ignition events at higher frequencies. **C. S. Wen et al.** [36]. An experiment was conducted to investigate the effect of the thickness and the axial location of an aluminum sheet on the DDT. The results are summarized as follows:

1) The presence of an aluminum sheet pre-triggered a detonation. 2) When using a smoked foil to visualize detonation cells, the thickness of the aluminum sheet must be less than 1.3mm (or 1.3% of the tube diameter). 3) A pre-triggered detonation was associated with the thickness of an aluminum sheet and its axial distance from the ignition end.

8. VALVING TECHNIQUES

Matsutomi, Yu et al. [37]. Developed a model to optimize the operational characteristics of valves less pulse detonation engine and analyzed the detonation propagation in the detonation tube and component geometries in different operating condition. As seen in this experiment the performance of valve less pulse detonation increases by proper handling TCPC. **Eric K. Anderson et al.** [38]. They used a novel valving technique to minimize the mechanical complexity and the weight of mixture metering system. As a result, the ball valve reduces the obstacle of intake flow and enhance the engine performance and efficiency. The ball valve offered dwindle to flow restriction in the incoming mixture of fuel. By using ball valve in PDE the C – J (Chapman-Jouguet) wave speed is less than the detonation wave speed measured for ethylene/air equivalence ratio from 0.8 to 1.0. **Ken Matsuoka et al.** [39]. Inflow driven valve system, a new valve system that uses in pulse detonation engine in which the maximum time averaged thrust of 22.6 N was achieved at an ethylene supply pressure of 0.95 MPa and an oxygen supply pressure of 1.9 MPa. The maximum specific impulse of 279 was achieved at an ethylene supply pressure of 0.8 MPa and an oxygen supply pressure of 16 MPa. **James T. Peace et al.** [40]. A fluidic valve with variable cavity length was fabricated and mounted on a PDE to simulate high-frequency operating conditions in order to understand its performance. A series of different cavity lengths was used. The tests were conducted in two phases. The first phase was with a blocked cavity and ambient conditions. The second phase had air injected from an upstream orifice at different pressures. The blocked cavity results indicated that a shorter cavity length decreased the occurrence of subsequent reflection that yielded a larger reflection pressure. For a fluidic valve with active injection, the interruption time depended on the injection pressure ratio. The chosen range of pressure ratios in this work showed an increase in interruption time with an increase in injection pressure ratio. They found that the chosen range of injection pressure ratio fell within a critical pressure ratio range where expected reflection of the incident shock from the contact surface between the injected dry air and detonation front was inconsistent.

9. IGNITION STUDIES ON PDE

Andrey Starikovskiy et al. [41]. Gave a method to control the ultra-lean, ultra-fast, low-temperature flames Non-equilibrium plasma demonstrates a great potential. In the case of radial propagation of the discharge with a low discharge power density, a slow flame was formed for successful DDT. For longitudinal discharges with a high-power density in a plasma channel; two fast DDT mechanisms have been observed. Plasma-assisted ignition might be an effective tool in different applications, including high-speed, ultra-lean combustion and control of transient combustion processes, such as the deflagration-to-detonation transition.

10. PARAMETERS & SPECIFICATION OPTIMIZATION

J. A. Roux [20]. The parametric cycle analysis was presented in terms of similar parameters to the well-known parametric cycle analysis for the ideal ramjet and turbojet engines. In this mathematical representation algebraic equations were used conveniently to investigate the ideal pulse detonation engine performance as a function of a variety of input parameters. The results showed the specific thrust performance of the ideal PDE to be superior to that of the ideal turbojet and ideal ramjet engines.

Brandon K. Kan [42]. Observed from the pulsed combustion events in a hypergolic pintle injector engine. Researchers have done two test series. In first test series they succeeded in reproducing violently pulsed combustion at the expense of instrumentation and hardware. In the second test series they progressed with medications to instrumentation and injector materials and demonstrated that the pulse combustion behavior was repeatable in behavior, amplitude response, and frequency response.

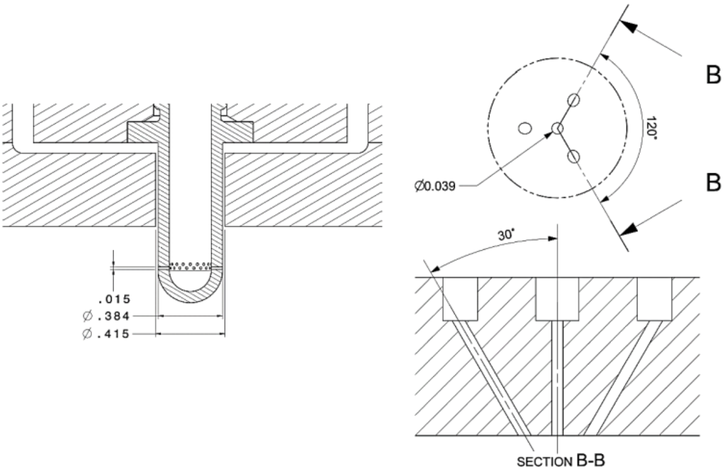

Figure 5. Schematic drawing of injectors with critical propellant flow path dimensions labeled [42]

The impinging jet injector used a reduced hydrogen peroxide concentration (90% H2O2) in comparison to the pintle injector (97% H2O2) and still produced the pulsed combustion behavior. They experimentally configured two main hardware in the first set of experimental hot fires using a pintle injector; whereas the second portion of test cases uses a three-element impinging tetrad injector which is shown in Figure 5 [42].

11. INSTRUMENTATION

Shinichi Maeda et al. [43]. By using several instruments, the scientists observed optically at a 1 μs frame speed a shock- induced combustion (SIC), a stable oblique detonation wave (ODW), and an intermediate wave structure containing a Straw-Hat type consisting of SIC and ODW. Broadly, there are two main types of Straw-Hat type propagating mechanism. The first is the case with no strong explosion at transition point and the ODW region slid back consistently relative to the projectile as the time increase resulting from being spread the SIC region. The second case is that in which the wave disrupted as a transition phenomenon but had almost constant wave structure during passing the observation region. The result of the experiment showed the possibility of existing of the unsteady sustaining mechanism of straw-Hat type.

12. THRUSTERS

Brandon Kan et. al. [44] designed and operated an open chamber hypergolic pintle thruster to produce high-frequency oscillations. Then Non-toxic hypergolic fuels of trig Lyme with sodium borohydride and 98% hydrogen peroxide were injected via the pintle in a fuel-centered configuration. The instrumentation used for recording the pulsed high-pressure, high-flame speed combustion events, the sampling rate for this is 100000Hz and captured the high-speed video at 5000fps. Initially, researchers showed the results as peak pressures beyond 3500 psi at frequencies of about 425 Hz to 600 Hz. They also planned to modify the test facility and improvise the instrumentation to accommodate these revelations including changing pintle material and installing higher-rated pressure transducers. Researchers concluded that the exact chamber phenomenon has not been characterized and they expected to use these experiments as guidelines to achieve repeatable detonations. The thruster tested in this phase of the research effort did not use actively modulated propellants for pulsed behavior; namely, a valveless approach that provides a potential to achieve repeatable, periodic behavior through the tuning of hydraulic circuits has been taken.

13. PARAMETERS AFFECTING SPECIFIC IMPULSE & THRUST (PASIT)

Cutler, Andrew D. [45]. They experimented a high-frequency pulse combustion actuator for aerodynamic flow control at high speed. The effect of fuel, air flow rates, tube length ranging from 203 to 406 mm injection frequency, and injection location were considered.

Maximum specific thrust was obtained with the tube operating in a roughly quarter-wave oscillation. The result demonstrates that there is an optimum injection frequency and equivalence ratio, in the range 0.5 to 0.6 for the configuration investigated, at which the specific thrust is maximized.

14. HYBRID & TURBINE INTEGRATION

Adam Rasheed et al. [46]. A multi-tube pulse detonation turbine system was analyzed in which the turbine efficiency under pulse detonation combustor fired operation was indistinguishable from steady performance within the approximately 8 point’s measurement uncertainty. The pulse detonation combustor turbine hybrid system demonstrated a potential 25% increase in efficiency. Furthermore, the turbine performance and overall rig performance were measured by performing five-minute runs to allow the PDC turbine hybrid rig to attain a thermal steady state.

Andrew C. St. George [47]. An investigation of previous studies involving turbines driven by pulsating, unsteady flows is conducted. The suitability of conventional steady flow performance metrics for application to the case of pulsating flow is discussed, with a focus on the observed deviation from quasi-steady behavior. This deviation is found to be a strong function of upstream geometry, pulse form and amplitude, and the disparity between the time scales of the pulse and of the rotor dynamics.

Existing studies exhibit controversy as to the effects of parametric variation of pulsating flow quantities on the turbine performance as well as suitable metrics to describe this performance. This study was used to predict the qualitative trends for the performance of an integrated pulse-detonation driven an axial turbine.

Kurt P. Rouser et al. [48]. An experiment was conducted on the radial turbine of GT28R driven PDE. The mass accumulation and expulsion were observed during the cycle. The results in this study showed that the formulation for turbine cycle-average specific work and mean effective isentropic efficiency were sensitive to pulsed detonation frequency, such that both measures of performance improved with increasing frequency. The mean effective turbine efficiency was about 40% at 30 Hz and produced the same power as an equivalent steady turbine operating at 61% indicating the potential for optimization of turbine design for pulse detonation engine.

15. APPLICATIONS

Eric M. Braun et al. [49]. A sustainable system which produces electricity from detonation driver piston integrated with a linear generator. In experimental studies, the maximum piston displacement, which affects energy and specific impulse, is dependent on all terms of the conservation of momentum equation and an enhancment in the piston mass and caused a rise in a specific energy output but not specific impulse. **Capt. Kaz I. Teope** [50]. Sets of experiments were accomplished to determine what magnitude of gas conductivity and power extraction could be attained from unseeded detonation driven combustion. (i) Phase one of the experiments was conducted using a pulsed detonation tube (PDT), extracting power across a load resistor in an electrical circuit with an applied voltage but no applied magnetic field. The experimental conductivity was seen to decrease with the source voltage, but the power increased with the source voltage. (ii) Phase two of the experiments was performed using a magnetic field to induce ion drift in the detonation trailing gas. The conductivity of the fluid decreased with increased load resistance while peak experimental power extraction increased with the lower load resistance.

16. CONCLUSIONS

This paper presents a comprehensive & detailed review of Pulse Detonation Technology worldwide. The paper also gives us a full spectrum analysis of various research areas related to PDE. One can easily study the obstacles used for DDT enhancements, various instrumentation predictions and test measurements of static and dynamic pressures inside PDE and valveless PDE’s, fuel-based studies on PDE, thermodynamic performance analysis, electric generation by detonations, pre-detonator analysis, numerical studies investigations related to pulse detonation turbine engines.

Pressure gain combustors are also one of the research areas of PDE for which researchers have developed algorithms and computations for detonations.

Thrust enhancement attachments like nozzles are also developed and studied in which nozzle shape is the key factor for selecting nozzles. The study on nozzle tells us about the use of a nozzle for PDE. Some technical notes on ejectors have also been categorized in which researchers study the shockwave phenomenon. Various optometry concepts were used in the past for this purpose.

Thrust measurement techniques are also studied and they evolved with time; nowadays fast response sensors are available in market for high-frequency operations of PDE. Hybridization of PDE was utilized in the past but not optimized for further experimental analysis. All these experimental studies are successfully applied to produce some serious results in the development of PDE.

Many applications are studied and proposed for PDE but due to system uncertain behavior, these are still in preliminary stages.

Some drawbacks lead to the abandoned research areas like. Thermodynamic analysis, optimization of various parameters of PDE like wave pressure, temperature, and density and mass flow to predict the propulsive performance of PDE.

Detonation wave engines or so-called the RDE (Rotating Detonation Engines) are the new study area for researchers starting from 2011. In this field, Russians claimed the successful running of RDE. No other organization produced such serious results in RDE’s area. It is hoped that this review provides a clearer picture of our current understanding and highlights the need for additional research on PDEs.

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