Technological advancements in Pulse Detonation Engine Technology in the recent past: A Characterized Report

Bharat Ankur DOGRA*[,1], Mehakveer SINGH[1], Tejinder Kumar JINDAL[1], Subhash CHANDER[2]

*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
[2]Terminal Ballistics Research Laboratory – TBRL,
Chandigarh, India-160003,
sckashyapa@gmail.com

DOI: 10.13111/2066-8201.2019.11.4.8

Received: 20 July 2019/ Accepted: 09 October 2019/ Published: December 2019

Abstract: *Pulse Detonation Engine (PDE), is an emerging and promising propulsive technology all over the world in the past few decades. A pulse detonation engine (PDE) is a type of propulsion system that uses detonation waves to combust the fuel and oxidizer mixture. Theoretically, a PDE can be operate from subsonic to hypersonic flight speeds. Pulsed detonation engines offer many advantages over conventional air-breathing engines and are regarded as potential replacements for air-breathing and rocket propulsion systems, for platforms ranging from subsonic unmanned vehicles, long-range transportation, high-speed vehicles, space launchers to space vehicles. This article highlights the operating cycle of PDE, starting with the fuel-oxidizer mixture, combustion and Deflagration to detonation transition (DDT) followed by purging. PDE combustion process, 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 paper is the extension of the previous study which is also a well characterized status report of PDE in different areas. The present study deals with the categorization of the design approach, computations & simulations, flow visualization, DDT & Thrust enhancement, PDRE's, experimental detonation engines with some of the experience and research undertaken in Punjab Engineering College under the complete supervision and guidance of Prof. Tejinder Kumar Jindal followed by applications of PDE technology.*

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 combustion utilized. As we go in the past, we find that First powered flight was accomplished by Wright Brothers in late 1903, on an aircraft driven by a reciprocating IC engine in the field of propulsion, the first turbojet-powered aircraft and 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/hr.

Mach number range of Gas turbine engines varies 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, ramjet and scramjet engines both 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.

On the other hand, PDEs 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 & RDE are in research fashion. Researchers from all over the world have moved to these propulsive technologies.

They have much interest in the historical background of PDE & RDE, 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 and some of them are the United States, Russia, Japan and China, Germany and Malaysia.

A characterized status report on PDE's given by Bharat et. al.[2] which 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. 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.

2. COMPUTATIONS, SIMULATIONS & CALCULATIONS

Ivan C. Ho et. al. investigated the accurate computational cell size to capture the behavior of transient detonation with a reduced kinetics mechanism. The experiment shows that the required computational cell size is order of ¼ of ZND induction length or 0.0625 mm was sufficient to capture the transient detonation behavior[3]. Daniel E. Paxson simulates the requisite principal of a detonative for turbine application and the numerous methods used to compute the flow field properties during refill and blowdown stages. In result, a complete wave diagram of the cycle is shown in Figure 1. Here, color contours of normalized pressure, temperature, velocity, and reactant fraction in the tube, over one period are plotted. The horizontal axis of each contour represents distance along the tube[4]. Daniel E. Paxson et. al. [5] Experimentally measured and numerically simulated the Cross flow heat load. The wall of pulse detonation engine tube which are heated substantially during operation in turn pre-heat the incoming detonable mixture.

This result increased the volumetric flow rates during tube filing, which leads in turn to overfilling and fuel spillage. William Stoddard, Andrew St. George et. al. carried out experiments as a follow up to prove the concept study of potential valvelessly self-aspirating static condition PDE designs without pressurized purge. They described the computational study of a configuration that after detonation would self-aspirate. For this, they proposed the evacuation of hot exhaust from the PDE tube, reduce the internal temperature below the auto ignition temperature of the fuel and bring the fresh air in. This allows for additional injection of fuel and shock initiation of a second cycle. A parametric study was completed to measure the effects of increased length of ejectors, aero valve spacing and ignition type. Aero valves have the ability to bias the direction of exhaust from a PDE. They determined the optimal spacing for the diameter of aero valve. Through some preliminary test conditions from the simulations they found this valve less PDE. As a result, there is an autoignition at high frequencies for direct detonation initiation even when purge was used. They found that up to 7 – 9 Hz, no purge portion of the cycle was needed to prevent auto-ignition of the next injection of fuel-oxidizer mixture without ejector. This proved the self-aspiration of fill fraction, ejector dimensions, location, and aero valve spacing, reliable detonations up to 15 Hz are possible, with 2/3 of the oxygen normally needed for this fuel flow [6].

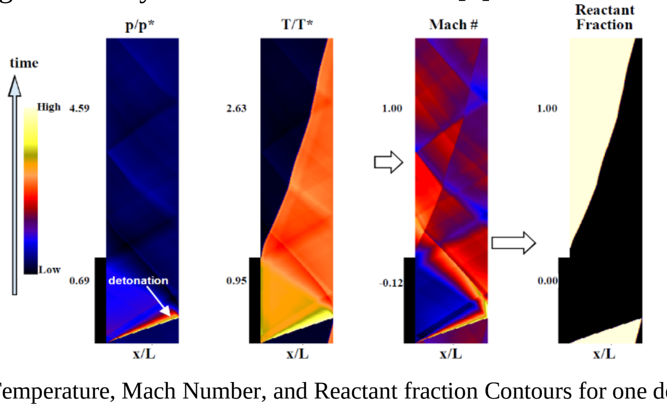

Figure 1. Pressure, Temperature, Mach Number, and Reactant fraction Contours for one detonation cycle [4]

Balaji Muralidaran et. al. [7] performed a Simulation of detonation interaction and unsteady shock with structures by applying an adaptive Cartesian cut cell approach for handling high speed reactive flow with moving structures. In conclusion the supersonic flow over cylinder test case, the cut cell approach accurately resolves embedded surface. William A. Stoddard et. al. [8] investigate the obstacle in a rotating detonation engine configuration by using computational fluid dynamics the test shown some feasibility in ramps as an obstacle in an RDE set-up for biasing the rotation direction of the flow and limiting the reversal and failures of the RDE. Dibesh D. Joshi et. al. [9] developed a 3-dimensional finite element model of PDE to study the effect of dynamic excitation and pulse to pulse interaction on the unsteady thrust generated and force reaction was calculated. The system transfer function initially validates and then the process of reconstruction aided in their deconvolution of calculated thrust signals from interference due to pulse to pulse interaction and dynamic excitation. Moreover, an inertial load was deducted from the deconvolved thrust signals to estimate the compensated thrust valve. Finally, the compensated impulse was used to calculate the specific impulse.

3. FLOW VISUALIZATION

A. B. Swantek et. al. [10] use several techniques to investigate void collapse such as particle image velocity meter and high-speed shadowgraph movies. In result, void exhibits the asymmetric collapse, with formation of a high-speed jet that originate from proximal wall of the void. Good collapse time agreement at high pressure ratio, but deviate at the lowest pressure ratio exhibit in simulation and experiment. Ken Matsuoka et. al. [11] performed a visualization experiment on single tube PDRE and double tube PDRE for thrust measurement. In the single tube PDRE system a stable time averaged thrust in a wide range of operation frequency (40 Hz- 160 Hz) and confirmed the increase of specific impulse due to a partial fill effect. At a maximum operation frequency of 159 Hz, the maximum propellant based specific impulse of 232 sec and maximum time averaged thrust of 71N. In the double tube PDRE system operational frequency per tube of 65 Hz and the propellant based impulse of 157 sec and a maximum time averaged thrust of 104N. Lefkowitz, Joseph et. al. [12] studied the repetitively pulsed nanosecond discharge on ignition time in a PDE where mixture of C2H4/air mixtures and aviation gasoline/air mixture at atmospheric pressure produced a maximum reduction in ignition time of 17% and 25%, respectively. The experiment showed that the ignition time reduced as total energy input while pulse repetition frequency increased. Schlieren imaging experiment revealed that the decrease in ignition time for high frequency discharge (<10 KHz) was due to the deposition of multiple discharge into a single ignition kernel. Brent A. Rankin et. al. [13] conduct a study on the unsteady exhaust plumes exiting from a turbine in PDE using radiation intensity measurements acquired with a high-speed infrared camera. Scientist demonstrates that imaging in the mid-infrared spectrum coupled with inverse radiation analysis is an effective non-intrusive technique for estimating gas temperature in low luminosity, unsteady, high speed flows of practical interest. Christopher A. Stevens et. al. [14] did an experiment on PDE to some interesting trends in the Mach number and separation distance as a function of the diffraction angle and corner radius. In result the process of re-initiation was highest when Mach number and ramp angle were high. The minimum Mach number needed for 100% detonation initiation was 4.0, and 44% initiation occurred at 3.5 for a 45-degree incline. Increasing the diffraction corner radius had significant effect on detonation reinitiating. Tomoki Uruno et. al. [15] conduct a study on the visualization of the detonation wave, shock wave and combustion wave that were generated by detonation diffraction and propagated through the narrow tube by using a high-speed camera. In the experiment the shock wave is attenuated as shock wave propagates through narrow tube and expand from narrow tube end and the propagation velocity could have similar tendency to attenuate as non-dimensional diameter normalized cell size decrease. Robert T. Fievisohn et. al. [16] analyze the internal flow field using shock-expansion theory along with the two-dimensional, isentropic method of characteristics (MOC). The resulting centered expansion fan is used to initialize a MOC solution. This analysis captures the bulk fluid occurring within the annulus of an RDE without the use of time-consuming numerical solutions. Fortunately, the MOC solution still runs much faster than current CFD simulations even with the added complexity.

4. DDT & THRUST ENHANCEMENT

Brophy, Christopher M. et. al. [17] showed that the swept ramp turbulence obstacles have the ability to detonate for short distance when a fully developed flame condition exists at the entrance to the obstacle field. The experiment was successful and enhance in the thrust value of 23 percent than the conventional spiral method. Aaron J. Glaser et. al. [18] observed in the pulse detonation engine the overall pressure loss in un-optimized configuration and due to the straight nozzle. Despite this the overall pressure gain in PDE by using the converging nozzle. The significant enhance in PR at both the head end and tail end combustor position provide by CVG AR=0.25 nozzle. Tae-Hyeong Yi et. al. [19] investigate four configurations of nozzles to find out the best shape and the effect of nozzle angle and length on its performance. In investigation divergent nozzle with angle 10 degree and the length 0.04 m is the best shape and minimum total pressure loss are achieved. Rotating detonation has negligible nozzle effect on propulsive performance, compared with that for pulse detonation engine. Eric Anderson et. al. [20] carried out the measurement of pressure drop across the valve, detonation wave speed, and detonation tube temperature in PDE were collected to verify successful operation of the engine. Results show that the ball valve presents significantly less obstacle to flow total pressure loss. There was no significant difference in DDT distance by using ball valve and it also exhibited longer ignition times about 1ms. B.W. Knox et. al. [21] found the effect of fluidic and physical obstacle for DDT in pulse detonation engine, where turbulence measurement shown that the fluidic obstacle generates approximately a 240% surge in turbulence intensity relative to physical obstacle. This results in reduction of ignition time by 45% which attribute to the increase in upstream turbulence intensity relative to the fluidic obstacle during the fill portion of the PDE cycle. This reduced ignition time represents shorter cycle times leading to greater thrust. Nobuyuki Tsuboi et. al. [22] studied the propulsive performance evaluated for the H_2/ Air PDE with an aerospike exhaust nozzle using multi-cycle two-dimensional limit cycle simulation. The result shows that the I_{spf} and F for the aerospike nozzle is 14% and 15% lower than those for the CD nozzle at M=2.1 and H=9.3 km. Most of the thrust for the CD nozzle is produced by the momentum thrust and the pressure thrust for the aerospike nozzle is approximately 30-50% of the momentum thrust. By an optimum nozzle configuration as well as the nozzle expansion ratio pressure thrust may be increased. C. M. Brophy et. al. [23] show the use of fluidic nozzles for pulse detonation combustors. They discussed the use of fluidic injection in the divergent portion of a c-d nozzle during the cyclic operation of a PDE. This research technique provides PDE's with a means to provide back pressurization, accelerate the exhaust products and generate adequate thrust coefficients. They experimentally tested the fluidic nozzle which is able to adapt to the extremely transient conditions of an impulsive detonation and the refresh conditions by injecting a small amount of air into the diverging section of the nozzle, effectively changing the nozzle area ratio during the cycle. A computational analysis has also been done to guide this research and experimental efforts allowed the fluidics to be visualized using a shadowgraph technique of a 2-d nozzle in a single shot detonation tube. Computational analysis of fluidic nozzle geometry has been performed for both sea level and altitude conditions with up to 12% of total mass flow rate being sent into the nozzle as a secondary flow. They find out that secondary air injection mass flow rates of less than 10% can produce noticeable improvements in the expansion process of a PD combustor. Nick D. DeBarmore et. al. [24] determined the flow behavior on T63 gas turbine engine nozzle guide vane in the exhaust flow of a six-inch RDE. It was shown that the static pressure drops over nozzle guide vane section is approximately 26.3 psi or 33.5%. It was clearly seen through FFT analysis that the pressure spike of the detonation propagates through the entire setup and into the NGV exhaust. Li, J Teo et. al. [25] The obstacle of orifice plate and vortex generators is investigated to achieve reliable and repeatable detonation in PDE. The result showed that initiation of DDT starting within vortex generator can enhance the DDT process and achieve a strong overdriven detonation. DDT transition generally takes place after the obstacle terminated; however, this transition can occur inside the obstacle when the vortex generator is used. Effectiveness of the DDT enhancement device depends on the operation frequency. Joseph P Mc Garry et. al. [26] shows an efficient solution to create turbulence through the use of a fluidic-based jet and the interaction of a laminar deflagrated flame with a fluidic jet. To initiate the early stages of the deflagration-to-detonation process the fluidic obstacle is issued to induce turbulence within the propagating flame in order. Schlieren imaging and particle image velocimetry are used to capture and analyze turbulence induction throughout the flame from the jet interaction. The jet eliminates pressure losses and heat soak effects induced by obstacles. Flow field and Schlieren measurements demonstrate that the jet is more effective at transitioning the flame flow from laminar to turbulent than the solid object is. James T. Peace et. al. [27] studied a series of PDE cases including a straight tube configuration and cases that featured conical diverging nozzles with expansion area ratios ranging from 1.25-2.5. It was determined that the addition of diverging conical nozzles increases the thrust and impulse for the cycle. Additionally, the specific impulse increases and appears to maximize in the nozzle expansion area ratio range of 2.25-2.5. However, it can be concluded that the propulsive performance was increased up to 21% with the addition of conical diverging nozzles.

5. PDRE (PULSE DETONATION ROCKET ENGINE)

Brandon K. Kan et. al. [28] detailed the Experimental results from a valveless pulsed detonation rocket engine concept with hypergolic propellants. This Experimental operation of a conceptual valveless PDRE with hypergolic propellants showed repeatable operational frequency of about 400 Hz for a baseline test condition while the pressure inside the chamber reached to 10,000 psi. Variable upstream feed pressures from the baseline test condition resulted in direct changes in pulsing frequency. Experiments conducted with a doubled chamber length showed little impact on peak pulsed pressures but indicated a 15% decrease in pulsation frequency. The data suggests that the pulsation frequency is dependent on dynamic orifice response, chamber dimensions (diameter and length), and the chemical ignition delay of the hypergolic propellant combination. Researchers also suggested for the performance improvement by either reducing the time between combustion initiation and blowdown or reducing the propellant flowed in each cycle. Experiments showed repeatable pulsed behavior with the need for robust injection techniques and instrumentation [28]. Ken Matsuoka et. al. [29] Researcher investigated the thrust performance of the PDR system and the thrust-to-weight ratio and confirmed the stable valve and PDE operation and continuous supplying of oxidizer, as designed. Propellant-based specific impulse of 131 s, time-averaged thrust of 256 N and thrust-to weight ratio of 0.8 were achieved in their experiments. The flight test used the newly-developed launch-recovery system. The system operated perfectly, and they successfully recovered the PDR without damage. The time-averaged thrust between launch time t = 1051 ms and t = 2000 ms was estimated at Fexp = 237 N, and the experimental propellant-based specific impulse was estimated at 106 s (81% of the ground test). Shunsuke Takagi et. al. [30] developed a four cylinder pulse detonation rocket engine system "Todoroki II". They developed the launch and the recovery system for a flight test along with a flight vehicle recovery winding system.

They proved that the flight test can be done repeatedly. In this flight test, the propellant mass flow estimated is m_p=229 g/s. A time average thrust is F_{ave}=254 N, the specific impulse of a propellant base is estimated to be I_{sp}, PF =113 s, this specific impulse is 86 % of a ground test. The factors of the inclination of Todoroki II may be that the number of ignitions differ in each combustion tube and the attitude of Todoroki II launched is tilted.

Considering these factors calculation results agree with experimental results in the attitude of Todoroki II. Ke Wang et. al. [31] introduced a novel control method to increase the operating frequency of PDREs.

They showed the conventional widely used TTL(transistor- transistor-logic) control signals solenoid valve and ignition [31] as shown in Figure 2.

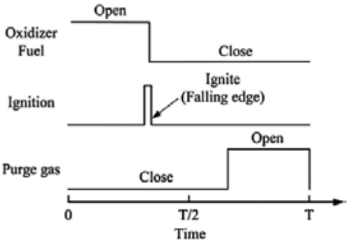

Figure 2. Conventional TTL control signals of supply and ignition

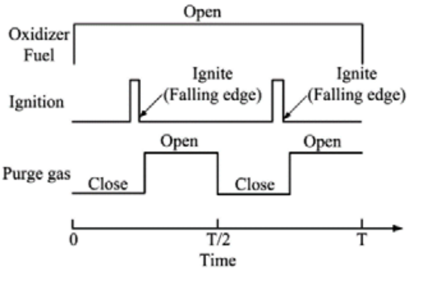

Figure 3. TTL control signals of supply and ignition for the double- frequency scheme

They also attempted to increase the operating frequency using the double frequency TTL control signal as shown in Figure 3.

For validation purpose they used the detonation tube comprising three sections i.e., an injection and mixing section, a DDT section, and a measurement section as shown in Figure 4.

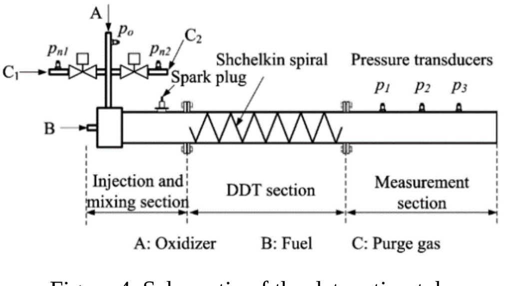

Figure 4. Schematic of the detonation tube

Unlike conventional control methodology, under which oxidizer and fuel valves were controlled by TTL signals similar to a purge gas valve as shown above in Figure 4, they were set open all the time during operations in this new method because solenoid valves could not close efficiently but with large leakage once exceeding a certain frequency. They validated the experiments to test the feasibility of such a control method. The achievable maximum operating frequency was 60 Hz when oxygen-enriched air, liquid gasoline, and nitrogen were used as oxidizer, fuel, and purge gas, respectively. The results indicated that it was feasible to increase the operating frequency of PDREs employing the new developed method [31]. **Ken Matsuoka et. al.** [32] developed a rotary-valve four-cylinder pulse detonation rocket engine system, Todoroki II. In a ground firing test with a duration of 1500 ms, a thrust-to engine-weight ratio of 2.7 was achieved. Todoroki II reached a height of about 9.7 m. The operation of the pulse detonation rocket engine under conditions simulating real vertical flight without constraint forces with a duration of about 1200 ms and a thrust-to-engine-weight ratio of 2.5 was demonstrated. Compared with the specific impulse at steady operation, the specific impulse of a high-response bipropellant thruster decreases 12–25% in a multi-pulse mode of 100 ms and 50% in a multi-pulse mode shorter than 10 ms. **Andrew Naples et. al.** [33] are the authors of a study where fuel feed pressure and flow velocity are temporally resolved and analyzed to determine coupling between the detonation channel and feed system. Results show that the detonation wave affects the injector feed resulting in flow variation throughout operation. Flow velocity measurement shows that fuel flowrate is modulated by the operation of the RDE. This means that equivalence ratio in the detonation channel likely varies throughout operation of the RDE. This can have drastic effects on operability and efficiency of the device.

6. EXPERIMENTAL DETONATION ENGINES

Bruno LE NAOUR [34] conducted an experiment on continuous detonation wave engine (CDWE) which shows higher theoretical performance than the classical iso-pressure combustion propulsion concepts, by using a mixture of (gaseous methane) GCH_4 & CH_2 with (gaseous oxygen) GO_2. To estimate the number of waves running within the chamber during nearly one second after ignition Bruno used fast acting pressure transducers. [34]. **Huan V. Cao et. al.** [35] conducted the parametric cycle analysis by integrating the continuous rotating detonation wave rocket (CRDWR) with modified ejector ramjet. The performance results of this particular engine in comparison to its regular rocket counterpart where the CRDWR gives more specific thrust and specific impulse than its regular rocket counterpart for two different flight trajectories while using the same initial temperatures and total pressure in the combustion chamber as well as CRDWR allows for a lower initial payload mass ratio.

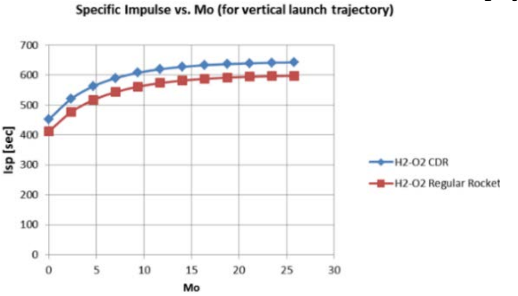

Figure 5. Specific impulse comparison between the CRDWR and its regular rocket counterpart in trans-atmospheric launch trajectory[35]

According to Figure 5, the CRDWR has also exceeded the specific impulse performance of its regular rocket counterpart along the trans-atmospheric launch trajectory. At sea level, the CRDWR has a 9.73 % increase in specific impulse over the regular rocket mode, and at high altitude, a 7.46 % increase in specific impulse is predicted.

7. PEC CHANDIGARH PDE RESEARCH

Aerospace Engineering Department of Punjab Engineering College (deemed to be University) located at Chandigarh, INDIA was working on the Pulse detonation Engine technology since 2010 under the guidance of Professor Tejinder Kumar Jindal (T. K. Jindal) from the same department. He coordinate many projects on this topic from various government agencies and achieve major goals in this research field. The very first research article published by Dr. T. K. Jindal gave an insight on application and different possible variants of Pulse detonation engines [36]. T. K. Jindal produced some results on stress analysis of PEC PDE tube [37] and analyzed the stresses developed for the type of material selected for the experimentation on Pulse detonation Engine. Subhash et. al. [38] studied and analyzed data from the data acquisition with noise from signal when 24V signal was given to the system. Subhash et. al. [39] gave a complete paper on the challenges faced during the integration of Pulse detonation Engine test-rig and its development. He also developed a simulation based environment on MATLAB which was helpful for predicting the behavior of PEC PDE [40]. Some research papers were also published in the field of fire control system done by Subhash et. al. [41] for the better understanding and experimental demonstration and integration of fire control system for Pulse detonation Engines. D. Mahaboob Valli et. al. [42] then published the thrust measurement of single tube valveless PDE which was tested in PEC itself. He presents the results obtained from PEC PDE for thrust values in different firing conditions. Then he gave a complete paper on optimization of various parameters of PEC PDE by applying one of the optimization technique called Taguchi tool and the thrust obtained from the experiments conducted according to Taguchi were analyzed with ANOVA (Analysis of Variance) technique [43]. Subhash et. al. [44] done a major research based on application of this PDE technology for SAM (surface to air missile) systems in which he investigated the theoretical and practical strategies for the development and analysis of SAM. He gave a complete PEC Chandigarh experience [45] in a research paper which deals with the basics and application of PDE, the challenges faced with their remedial follow up’s. Bharat et. al. [46] gave a configuration design for Pulse detonation combustor that showed and helped in developing the PDE test-rig. Bharat et. al. [47] studied about the various fuels used in PDE that deals with a complete review on this topic.

8. APPLICATIONS

Eric M. Braun et. al. [48] experimented and designed a sustainable system which produce 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 enhance in the piston mass caused a rise in a specific energy output but not specific impulse. Bharat et. al. [49] gave a feasibility study and numerical approach on power production based on Pulse Detonation Engine technology. Capt. Kaz I. Teope. [50] accomplished sets of experiments to determine what magnitude of gas conductivity and power extraction could be attained from unseeded detonation driven combustion. (i) Phase one experiments were 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 source voltage, but the power increased with source voltage. (ii) Phase two experiments were 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 lower load resistance.

9. CONCLUSIONS

This paper presents various technological advancements in the field of Pulse Detonation Engine Technology. This paper is the remaining version of the paper published earlier in the INCAS bulletin under the title "A Characterized Status Report on Pulse Detonation Engine" which gives a detailed review of pulse detonation engine from almost every corner of the world.

This paper also gives a full spectrum analysis of various research areas related to PDE. One can easily study the computational simulations on PDE worldwide, flow visualization techniques and methods used, deflagration to detonation transition techniques used for the enhancement of PDE parameters along with thrust enhancement techniques. This research article also highlights various research conducted on rockets i.e. Pulse detonation Rocket Engines (PDRE's) and experimental detonation engines on which a number of researchers had successfully conducted numerous experiments on Pulse detonation technology.

By examining and thoroughly studying these research areas PEC (Punjab Engineering College) Pulse Detonation Research lab has also started R & D in 2012. PEC started working on PDE from the scratch, done all the development from the base level without referring any outside help and in a much more economical way. Prof. T. K. Jindal started working on it, then some other researchers joined them for further work. PEC AERO PDE lab has shown serious research in this area by developing an in-house fully optimized, PDE test-rig with in-house developed controller circuit & system. For instrumentation purpose, we used NI and AIMIL DAQ's with PCB quartz sensors for measurement and data generation. On this PDE test-rig, one can perform multiple experiments with optimized PD (Pulse Detonation) tube. Though there are some drawbacks that 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 but the research exploration on PDE's are still in race all over the world to find new avenues and research areas in the field of propulsion. It is hoped that this review provides a clearer picture of our current understanding and highlights the need for additional research on PDEs.

REFERENCES

[1] J. D. Carter and F. K. Lu, Experiences in Testing of a Large-Scale, Liquid-Fueled, Air-Breathing, Pulse Detonation Engine, no. August, pp. 1–14, 2011.

[2] B. A. Dogra, M. Singh, and T. K. Jindal, A Characterized Status Report on Pulse Detonation Engine, *INCAS Bull.*, vol. **11**, no. 2, pp. 69–83, Jun. 2019.

[3] J. O. Ho, Ivan C Sinibaldi, Determination of Practical Computational Cell Size Requirements for Simulation of H 2 -Air Detonations in Pulse Detonation Engines, no. January, p. 93943, 2010.

[4] D. E. Paxson, A Simplified Model for Detonation Based Pressure-Gain Combustors, *46th AIAA Jt. Propuls. Conf.*, no. July, pp. 1–11, 2010.

[5] D. E. Paxson, A. G. Naples, J. L. Hoke, F. Schauer, and S. Engineer, Numerical Analysis of a Pulse Detonation Cross Flow Heat Load Experiment, no. January, pp. 1–12, 2011.

[6] W. Stoddard, A. S. George, R. Driscoll, and E. J. Gutmark, Experimental Optimization of Static Valveless Self-

Aspiration of a Pulse Detonation Engine, no. August, pp. 1–10, 2012.
[7] B. Muralidharan and S. Menon, Simulations of Unsteady Shocks and Detonation Interactions with Structures, *49th AIAA/ASME/SAE/ASEE Jt. PropulsionConference*, pp. 1–13, 2013.
[8] W. A. S. and E. J. Gutmark, Numerical Study of Obstacles in Rotating Detonation Engines, no. January, pp. 1–8, 2013.
[9] D. D. J. and F. K. Lu, Study of Unsteady Thrust Characteristics of Pulse Detonation Engines, *J. KONES*, vol. 18, no. 3, pp. 515–521, 2011.
[10] A. B. Swantek, R. K. Shukla, and J. M. Austin, Effect of Loading Wave Profile on Hydrodynamic Void Collapse in Detonation Initiation, *Ultrasonics*, no. January, pp. 1–14, 2010.
[11] K. Matsuoka, M. Esumi, K. B. Ikeguchi, and J. Kasahara, Thrust Measurement and Visualization Experiment of a Multi-Cycle Single-Tube Pulse Detonation, *AIAA*, no. August, pp. 3–14, 2011.
[12] J. K. Lefkowitz, Y. Ju, C. A. Stevens, T. Ombrello, F. Schauer, and J. Hoke, The Effects of Repetitively Pulsed Nanosecond Discharges on Ignition Time in a Pulsed Detonation Engine, *49th AIAA/ASME/SAE/ASEE Jt. Propuls. Conf.*, pp. 1–19, 2013.
[13] B. A. Rankin, Radiation Measurements and Temperature Estimates of Pulsed Detonation Combustion, in *51st AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*, 2013, pp. 1–13.
[14] C. A. Stevens, P. I. King, F. R. Schauer, and J. L. Hoke, An Experimental Study of Detonation Diffraction and Shock Initiation, in *51st AIAA Aerospace Sciences Meeting*, 2013, pp. 1–19.
[15] T. Uruno, S. Maeda, and J. Kasahara, Study on Detonation Wave Attenuation through Narrow Tube for Application to Explosion Safety and Detonation Engines, in *51st AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition 07 - 10 January*, 2013, pp. 1–13.
[16] R. T. Fievisohn and K. H. Yu, Method of Characteristics Analysis of the Internal Flowfield in a Rotating Detonation Engine, *53rd AIAA Aerosp. Sci. Meet.*, no. January, pp. 1–8, 2015.
[17] C. M. Brophy, Initiation Improvements for Hydrocarbon / Air Mixtures in Pulse Detonation Applications, *47th AIAA Aerosp. Sci. Meet. Incl. New Horizons Forum Aerosp. Expo.*, 2009.
[18] A. J. Glaser, A. Rasheed, R. Dunton, and V. Tangirala, Measurement of Pressure-Rise in a Pulse Detonation Engine, no. January, pp. 1–16, 2009.
[19] T. Yi, J. Lou, C. Turangan, and P. Wolanski, Effect of Nozzle Shapes on the Performance of Continuously Rotating Detonation Engine, no. January, p. 2010, 2010.
[20] E. A. C. A. J. L. H. Stevens, Ball Valve Pulsed Detonation Engine, no. January, pp. 1–9, 2007.
[21] B. W. and D. J. F. Knox, A Comparison of Fluidic and Physical Obstacles for Deflagration-to-Detonation Transition, *Solutions*, no. 10649, pp. 1–9, 2011.
[22] N. Tsuboi and Y. Kawakami, Numerical Study and Performance Evaluation for Pulse Detonation Engine with an Aerospike Nozzle, no. January, pp. 5–10, 2011.
[23] C. M. Brophy, D. F. Dausen, L. R. Smith, and R. G. Wright, Fluidic Nozzles for Pulse Detonation Combustors, *Time*, no. January, pp. 1–12, 2012.
[24] N. D. DeBarmore, P. I. King, F. R. Schauer, and J. L. Hoke, Nozzle Guide Vane Integration into Rotating Detonation Engine, *AIAA Aerosp. Sci. Meet. Incl. New Horizons Forum Aerosp. Expo. 51st*, no. January, pp. 7–10, 2013.
[25] J. Li, C. J. Teo, K. S. Lim, C. Wen, and B. C. Khoo, Deflagration to Detonation Transition by Hybrid Obstacles in Pulse Detonation Engines, pp. 1–12, 2013.
[26] J. P. Mcgarry and K. A. Ahmed, Laminar Deflagrated Flame Interaction with a Fluidic Jet Flow for Deflagration-to-Detonation Flame Acceleration, pp. 1–15, 2015.
[27] J. T. Peace and F. K. Lu, Numerical Study of Pulse Detonation Engine Nozzle and Exhaust Flow Phenomena, *51st AIAA/SAE/ASEE Jt. Propuls. Conf.*, pp. 1–13, 2015.
[28] B. K. Kan and S. D. Heister, Chamber Volume Effects on Hypergolic Pulse Detonation Rocket Engine, *50th AIAA/ASME/SAE/ASEE Jt. Propuls. Conf.*, pp. 1–11, 2014.
[29] K. Matsuoka *et al.*, Study on a Rotary-Valved Four-Cylinder Pulse Detonation Rocket: Six Degree-of-Freedom Flight Measurement 1, *52nd Aerosp. Sci. Meet.*, no. January, pp. 1–9, 2014.
[30] S. Takagi *et al.*, Study on Pulse Detonation Rocket Engine Using Flight Test Demonstrator Todoroki II, pp. 1–12, 2014.
[31] K. Wang, W. Fan, W. Lu, and F. Chen, One Method to Increase the Operating Frequency of Pulse Detonation Rocket Engines, *J. Propuls. Power*, vol. **30**, no. 2, pp. 518–522, 2014.
[32] K. Matsuoka, T. Morozumi, S. Takagi, J. Kasahara, A. Matsuo, and I. Funaki, Flight Validation of a Rotary-Valved Four-Cylinder Pulse Detonation Rocket, *J. Propuls. Power*, pp. 1–9, 2015.
[33] A. Naples, J. Hoke, and F. Schauer, Experimental Investigation of a Rotating Detonation Engine Injector Temporal Response, *53rd AIAA Aerosp. Sci. Meet.*, no. January, pp. 1–7, 2015.

[34] B. Le Naour, Recent experimental results obtained on Continuous Detonation Wave Engine, *Chief Eng.*, no. April, pp. 1–7, 2011.

[35] H. V Cao, Parametric Cycle Analysis of Continuous Rotating Detonation Ejector-Augmented Rocket Engine, in *49th AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, American Institute of Aeronautics and Astronautics, 2013.

[36] T. K. Jindal, Pulse Detonation Engine - A Next Gen Propulsion, *Int. J. Mod. Eng. Res.*, vol. **2**, no. 6, pp. 4083–4085, 2012.

[37] T. K. Jindal, Stress Analysis of Pulse Detonation Engine Tube, *Int. J. Mod. Eng. Res.*, vol. **2**, no. 6, pp. 4080–4082, 2012.

[38] T. K. Jindal, Effect of 24 V Control Pulse on the Data Acquired In a Pulse Detonation Engine Test, *Int. J. Adv. Res. Electr. Electron. Instrum. Eng.*, vol. **1**, no. 4, pp. 212–217, 2012.

[39] S. Chander and T. K. Jindal, Integration Challenges in Design and Development of Pulse Detonation Test Rig, *Int. J. Adv. Res. Electr. Electron. Instrum. Eng.*, vol. **1**, no. 4, pp. 291–304, 2012.

[40] D. M. and D. T. J. Subhash Chander, Multiple Option Levels Based Full Function PEC Aero Simulation (PAeroSim) Development for Pulse Detonation Engines & Systems, Sarod, pp. 1–10, 2013.

[41] S. Chander and T. K. Jindal, Design of Automated Fire Control System for C 2 H 2 / O 2 Pulse Detonation Rig, vol. **2,** no. 2, pp. 924–932, 2013.

[42] D. M. Valli and T. K. Jindal, Thrust Measurement of Single Tube Valve less Pulse Detonation Engine, *Int. J. Sci. Eng. Res.*, vol. **4**, pp. 1–8, 2013.

[43] D. M. Valli and T. K. Jindal, Application of Taguchi Method for Optimization of Physical Parameters Affecting the Performance of Pulse Detonation Engine, *J. Basic Appl. Eng. Res.*, vol. **1**, no. 1, pp. 18–23, 2014.

[44] S. Chander and T. K. Jindal, A study of possible technical aspects needed to be addressed in respect of system engineering of surface to air missile by application of pulse, *IJME*, vol. **1**, no. 1, pp. 40–43, 2014.

[45] A. P. Subhash Chander, Research Scholar and T K Jindal, Pulse Detonation Propulsion System - PEC Chandigarh Experience, in *National Conference on Innovative Trends in Mechanical and Aerospace Engineering (ITMAE-2014) Pulse*, 2017, vol. **91**, pp. 399–404.

[46] B. A. Dogra and T. K. Jindal, Configuration Design of Pulse Detonation Combustor, *Int. J. Eng. Adv. Technol.*, vol. **6**, pp. 135–139, 2017.

[47] A. S. Jayoria, B. A. Dogra, and T. Jindal, Various fuels used in pulse detonation engine-A review, in *5th National Symposium on Shock Waves, February 26-28*, 2018, pp. 1–9.

[48] E. M. Braun, F. K. Lu, and N. P. Technology, Proof-of-Principle Detonation Driven, Linear Electric Generator Facility, July, 2010.

[49] T. K. Jindal, Bahrat Ankur Dogra, Developmemt of pde based power generation configuration, in *international conference on Science, Technology, Engineering and Msthematics*, 2017.

[50] K. Teope, P. King, F. Schauer, and J. Hoke, Experimental Magnetohydrodynamic Energy Extraction from a Pulsed Detonation Tube, in *53rd AIAA Aerospace Sciences Meeting*, American Institute of Aeronautics and Astronautics, 2015.