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Innovative Trends in Pulse Detonation Engine, its Challenges and Suggested Solution

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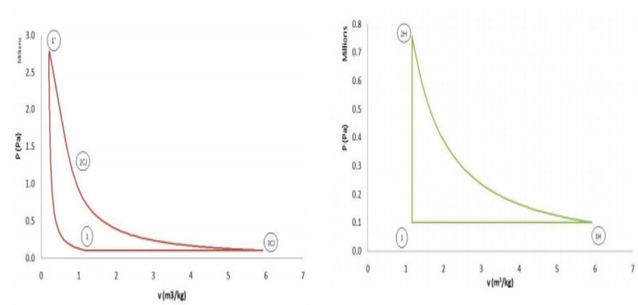
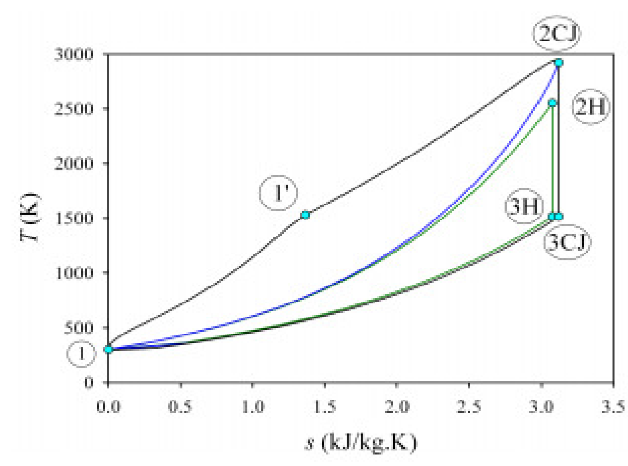
Abstract: **Pulse detonation engine (PDE) is an air-breathing intermittent combustion engine in which detonations are triggered at high frequencies through simultaneously burning and accelerating the fuel-air mixture. The generation shock waves are driven through a tube, creating a thrust. Shock Waves inside engine travels at either at subsonic or supersonic speed depending upon the physical parameters of tube, frequency of detonation and rate of injection of air-fuel mixture in the tube. Pulse detonation engine is getting considerable attention because of their superior performance parameters such as thermal efficiency and thrust/weight ratio over current traditional Rocket engine[1]. In this paper, the status of the theoretical and experimental study of Pulse Detonation Engine is presented. Secondly, a comparison of thermal efficiency of Pulse detonation Engine and generally used propulsion system (such as Rocket Engine) is studied and it is shown that efficiency of Pulse Detonation Engine is much higher. Also, the other advantages of Pulse Detonation Engine are discussed. Further, this paper presents a theoretical investigation of the problems preventing the widespread use of Pulse detonation Engine. In the end, a review of various methods which may overcome these challenges is provided, specifically, the approach of Detonation to Deflagration (DDT) method for solving Detonation Initiation problem is discussed in detail. The paper ends on a note of promising near future when Pulse Detonation Engines will become the staple for power generation and locomotion.**

1. INTROD ASHISH DHIMAN UCTION

The Pulse detonation engine is realized by the phenomenon of rapid burning or material conversion rate, typically tens of thousands of time faster than in a flame. This rapid burning of the air-fuel mixture results in a scenario where 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 [3]. This phenomenon is shown in the three thermodynamic cycles (constant pressure, constant volume and detonation) in Figure 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 above data we can conclude that the thermodynamic efficiency of the detonation cycle is close to that of the constant volume cycle. It must be noted that the physics of detonation is not accurately captured by constant volume cycle. Although the graph of constant volume cycle closely resembles the detonation phenomenon, Detonations are more simply explained by the Zel'dovich–von Neumann–Doring model or ZND model which takes into account the pressure increase along the detonation wave front due to shock wave travelling [10-11].



Φιγυρε 1– Πς διαγραμ οφ (α) ΖΝΔ Χψχλε (β) Ημπηρεψ χψχλε

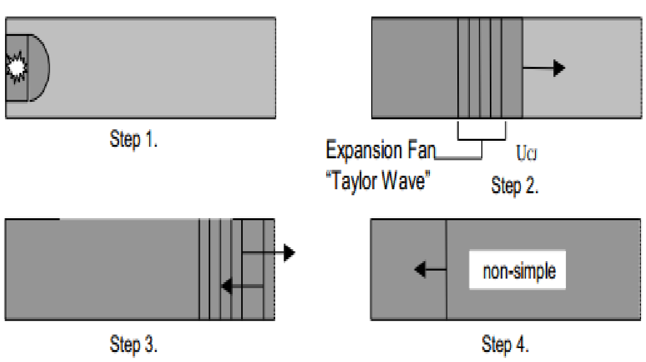


Φιγυρε 2 – ΤΣ Διαγρεμ Ημπηρεψ (1–2Η–3Η–1) ανδ ΖΝΔ (1–1 ̄2Χϑ –3Χϑ –1) χψ χλεσ

It is safe to assume that theoretically the thermal efficiency of Detonation is even higher than constant volume cycle. As we can see from the TS graph that heat addition during the Humphrey (Constant Volume) cycle is less than the heat addition during the ZND cycle by an amount of energy added extra due to pressure increase along the line of heat addition. Thus, as we can infer from the graph, the detonation cycle is theoretically the highest efficiency cycle in propulsion systems. This is the basic cycle that is used in the Pulse Detonation Engine. Therefore it is important to harness energy from our limited resources through this cycle so that maximum output is extracted and wastage of our resources is as minimum as possible.

2. BASIC WORKING

A pulse detonation engine is an unsteady propulsive device that contains four major steps per cycle. These steps appear in Figure 3. The first step consists of filling a combustion chamber with combustible gases and initiating detonation. In the second step, the detonation wave propagates to the open end of the tube followed by the Taylor wave. Taylor wave is an unsteady expansion wave propagating towards the closed end of the tube. The Pressure, Temperature and Flow velocity reduces due to this Taylor Wave and this wave is responsible to thwart the flow near the closed end of tube [15]. The third step begins with the reflection of the expansion wave off the interface. This reflected expansion immediately interacts with the Taylor wave, while the products begin to exhaust the tube. The fourth step consists of the first characteristic of the reflected expansion reaching the front wall of the tube thus decreasing the pressure at this wall. Quasi-steady thrust levels can be achieved by repeating this cycle at relatively high frequency and/or using more than one combustion chamber operating out of phase.



Φιγυρε 3 – Φουρ στεπσ οφ α πυλσε δετονατιον ενγινε χψχλε

3. PROBLEMS ASSOCIATED

The simplicity of the PDE concept is somewhat misleading; a number of fundamental issues which have rarely been addressed in engine development or detonation science must be resolved for the successful development of PDE devices. Although there will be a plethora of issues to be resolved before Pulse Detonation Engine can be demonstrated for pragmatic use, however, we will note only a limited number of the issues that will need to be resolved for engine feasibility demonstration. These issues are primary concern for current generation of scientists and a substantial amount of attention is required over these problems.

3.1 Detonation Initiation

In order to start the process stated above, the basic requirement of the cycle is to start ignition in gas filled chamber such that they can later be converted to detonation waves. This process of starting ignition inside chamber to cause detonation is called as Detonation Initiation. Scientists have been trying to find a way for detonation initiation that will require least amount of energy and gives result close to ideal detonation cycle[1-2]. This process can be done by Direct Detonation Initiator. A detonation initiator starts the detonation wave front required for compression of the charge at supersonic velocity producing relative isochoric conditions. Detonation Initiation can be done by Direct Initiation i.e. giving energy to the closed end of tube to start detonation. But, this requires huge amount of energy which would reduce the engine efficiency [5]. Another initiation method is known as DDT (Deflagration to Detonation). In this method first deflagration (Combustion at subsonic speed) is started in the tube and the waves are then traveled along the tube to turn into supersonic waves i.e. detonation waves. Deflagration to Detonation begins with a deflagration initiated by some relatively weak energy source which accelerates through interactions with its surroundings into a coupled shock wave-reaction zone structure characteristic of a detonation. But, after a small spark has created a deflagration, the transition process can take several meters or longer and a corresponding large amount of time. This transition delay can cause problems such engine shut- off or knocking [6]. The key to detonation initiation schemes applicable to pulse detonation engines is to significantly shorten the distance and time required for deflagration-to-detonation transition.

3.2 Thrust Extraction & Measurement

Thrust Extraction is one of the most crucial elements for design of Pulse Detonation Engine. Thrust is the final output we require from the engine and it should exceed than its predecessor engines. Following common practice, the propulsive performance of a PDE can be characterized by the specific impulse, defined as the thrust per unit weight flow rate of fuel or the impulse per unit weight of fuel [4]:

$$I_{sp} = \frac{\bar{F}}{\bar{\dot{m}}_f g} = \frac{I}{m_f g}$$

There are many different types of design are available for Pulse Detonation Engine which produce different types of thrust. Unfortunately, most of these designs did not produce experimental studies for direct thrust measurements. In some cases, the thrust was calculated based on pressure data collected during a single cycle from one transducer located on the thrust wall. We would like to point out that direct measurement of thrust is absolutely essential for establishing engine feasibility and studying its efficiency and performance characteristics. Since thrust in a PDE device is produced by integrating a set of intermittent impulses exerted in the direction of motion, we can envision a system where pressure at the thrust wall will not generate thrust in the direction of motion or will generate thrust inefficiently. Some engine elements can generate negative thrust, thus significantly reducing overall output. Thus, direct measurement of thrust generated by engine operation should be an element of every serious experimental study of engine performance.

3.3 Mixture Injection and Mixing System

Detonability limits for the fuel/oxidizer mixtures are generally narrower than limits for combustion. In addition, properties of the detonation waves and conditions for their propagation, and the energy required for initiation, will rapidly change as a function of the fuel/oxidizer ratio. Thus, for reliable operation, PDE should have a fuel/oxygen injection and mixing system that can maintain mixture concentration in narrow limits. PDE cycle frequency is mostly controlled by mixture injection and mixing processes[10-12]. Typically the detonable mixture should move through the detonation chamber volume at velocities lower than 100 m/sec [7]. At these velocities, injection and mixing of gaseous fuels does not present a problem. Furthermore, the mixture velocity can be reduced and frequency and mixing efficiency increased by using a set of injectors that are distributed along the chamber wall [13].

One of the issues that can be critical for injection of gaseous fuels is the lag time introduced by the volume of gas located between the flow control valve and injection ports. In some cases this will impose significant limits on the PDE operating frequency. If the operating frequency of PDE is around sub-sonic speed, then high efficiency at supersonic speed could not be attained. To bypass this problem, we can use systems that inject liquid fuels, which usually will have a negative effect on mixing efficiency and detonability. Fortunately many aspects of intermittent injection and mixing can be analyzed using detailed numerical simulations for design of these systems.

3.4 Cycle Losses

Nonsteady flows are generated to some extent in a large number of conventional steady propulsion devices and are usually associated with efficiency losses [11]. A device, Compex supercharger, used for increasing efficiency of PDE, uses the high pressure of the hot gases exiting the diesel engine combustion chamber to compress fresh air in a set of shock tubes. There are a number of devices that use acoustic waves for enhanced combustion efficiency and propulsion, including the V-l pulse-jet engine and high-efficiency pulsed combustors for house heating [14].

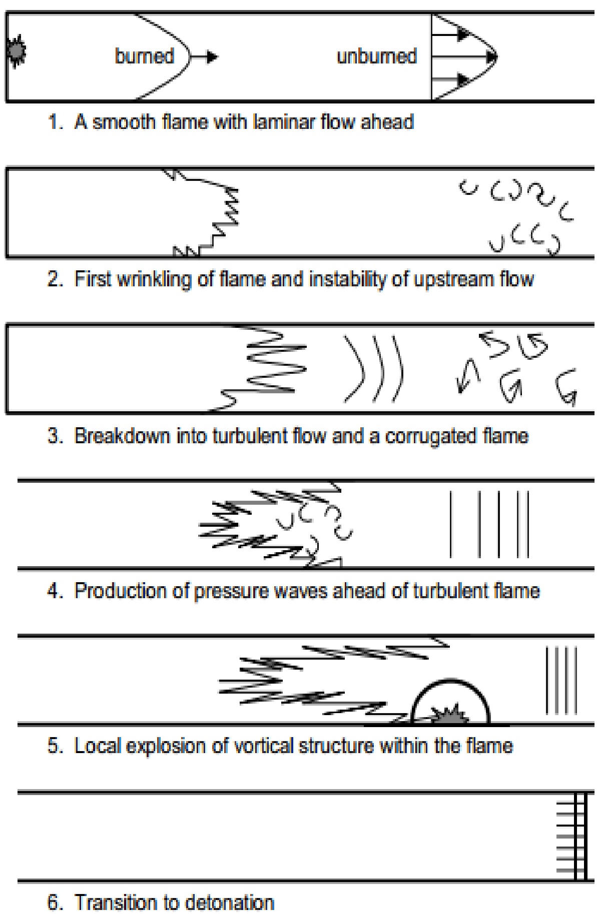
The theory of steady-state propulsion devices is well developed. On the simplest level, we-can analyze these devices by determining the properties of a unit volume of working fluid at different stations as it flows through the engine: inlet, compressor, combustion chamber and turbine [7]. Many elements of steady-state engines are universal even for engines with very different designs. At the same time, nonsteady devices differ more radically from one another. For example, Comprex and Pulse-Jet have very little in common. Thus, analysis of every nonsteady concept should be device-specific for most elements of the device. Additional difficulties are caused by flow discontinuities and non-uniformities that vary in time and interact in a complex manner with the engine boundaries. Only a few references make an attempt to deal with some nonsteady devices. At present comprehensive numerical simulations of nonsteady devices are possible using CFD methods. The current status of CFD research allows consideration of complex device geometry as well as a detailed account of the physical and chemical process.

4. FEASIBLE SOLUTION

4.1 Detonation Deflagration Transition

A detonation may be initiated by two different modes: deflagration-to-detonation transition and direct initiation.

A key issue in detonation initiation from Direct Initiation is the high energy required to start the ignition. The amount of energy required to generate the detonation is significantly high to reduce the overall efficiency of the Engine. Secondly, the PDE requires detonation at subsonic as well as supersonic speed. At Supersonic speed, it is difficult to obtain continuous detonation at high energy and thus can lead to Engine fire missing. A key issue in pulse detonation engine development is a low-energy initiation system that produces a short run-up distance to detonation and has reproducible shot-to-shot performance. Current practice in designing detonation initiation systems based on deflagration-to-detonation transition is highly empirical and no design guidelines are available. Due to these reasons, DDT approach to Detonation is more rigorously studied. Refer Figure 4, a detonation, formed in a tube that is ignited at a closed end, begins with a combustion wave that accelerates due to heating of the unburned gases ahead of the wave. This heating occurs from successive compressive waves formed from the expansion of the burned gas products, which have a specific volume that is 10-15 times greater than the unburned gases ahead of the flame. The higher temperature of the unburned gases causes the sound velocity to increase enabling the succeeding waves to catch up to the initial wave. The higher temperature in the unburned gases also contributes to increasing the flame speed, accelerating the unburned mixture. Turbulence in the gas mixture inside the combustion chamber is an important characteristic of any Gas Turbine engine in order to increase the flame front speed and overall efficiency of detonation [7-8]. Measure of turbulence is the Reynolds Number of the flow, higher the Reynolds Number greater turbulence in the flow [9]. Turbulence in the flow initiates due to this unburned gas acceleration, the natural instability of high Reynolds number flows and the vortices associated with flow over defects or obstructions in the tube. This turbulence causes a distortion of the flame front. As flow turbulence in the tube increases, additional increases in the velocity and acceleration cause the formation of additional compression waves in addition to further distorting the flame front separating it into distinct sheets.



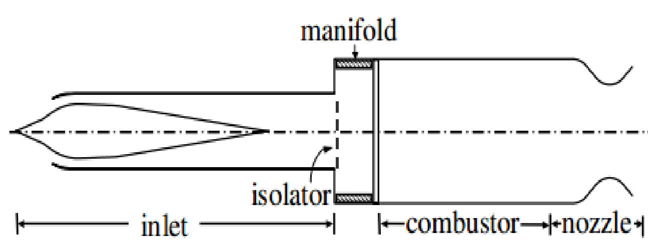
Φιγυρε 4– Τρανσιτιον φρομ Δεφλαγρατιον το Δετονατιον.

The positive feedback between the flame and the flow ahead of it progresses to a point where the flame breaks into a distributed reaction zone with strong straining motions and large fluctuations in the temperature and species concentrations at the characteristic flame scale length. Some portions of the flame front are extinguished due to the locally high strain rates. As parts of the previously extinguished mixture re-ignite in the form of exploding eddies; weak shock waves are formed ahead of the front. At this point the burning rate increases slightly and the interaction of reaction waves, hotspots, and the amplification of weak shock waves results in the reactants exploding close behind the shock. This energy release is sufficient to maintain the shock's strength, thus forming a detonation.

4.2 Thrust Extraction Module

Figure 5 shows schematically the system under consideration. It includes a coaxial supersonic inlet, an air manifold, a valve, a combustion chamber consisting of single or multiple detonation tubes, and a common convergent–divergent (CD) nozzle. The manifold provides a buffer zone between the inlet and combustor, in which fuel and air are mixed before entering the combustor. The inlet is designed to capture and supply a stable airflow at a rate demanded by the combustor and to maintain a high-pressure recovery and stability margin at various engine operating conditions.

The flow loss resulting from the valve operation and reactant distribution should also be considered. A rigorous assessment of such a loss requires substantial computational efforts that may not be justified in the present study. The issue of nozzle optimization remains unresolved due to difficulties arising from the inherent flow unsteadiness in a nozzle and its strong interaction with other parts of an engine. Ideally, the nozzle configuration should adapt itself to the instantaneous local flow conditions [14]. It is, however, formidable to design and fabricate such a flexible nozzle with adaptation on time scales commensurate with the PDE operation. Although not strictly proved, a CD nozzle appears to be more suited for PDEs than other configurations because of the advantages of preserving the chamber pressure during the Blow down and filling processes and providing more thrust surface area during the exhaust of detonation products [4].



Φιγυρε 5 – Βασιχ Τηρυστ εξτραχτιον Μοδυλε

4.3 Valve-less PDE

To prevent inlet unstart caused by high-pressure detonation products, PDEs generally require an inlet/combustor interface to prevent the combustor flow from traveling into the inlet during certain periods of the operation cycle. Based on how this interface is realized, PDEs can be classified as either valved or valve-less. In the valved design, the interface is a mechanical valve located at the head end of the detonation tube. The valve is closed during detonation initiation and propagation, as well as the blowdown stage, but remains open during the chamber filling and purging stages. The stagnation of the airflow during the valve-closed period leads to some performance loss, although the problem may be mitigated by using multiple detonation tubes [12]. In the valve-less design, the isolation between the inlet and the combustor is achieved through gas-dynamic means, such that no valves are required for controlling the air delivery into the combustor [12-13].

The system is mechanically simpler and circumvents the disadvantage associated with airflow stagnation in the valved design. The inclusion of a gas-dynamic isolator, however, may considerably limit the engine operation frequency. Until recently, most studies have focused on the flow dynamics and propulsive performance of valved PDEs, with only limited efforts on valveless PDEs. But now, considerable attention is being given to valveless Pulse Detonation Engine and it seems to bring promising results in the advancement of research in PDEs.

5. CONCLUDING REMARKS

As briefly reviewed above, research on Pulse detonation Engine has been extensively done because of its theoretical advantage of higher Thermal efficiency and Mechanical Simplicity. Pulse detonation propulsion technology may become an attractive option for missile, air, and space transportation systems in the 21st century if current scientific and engineering obstacles are successfully addressed. Because detonation is an extremely efficient means of burning propellant mixtures to release the chemical energy content, pulse detonation propulsion technology is anticipated to yield a greater performance payoff than other competing technologies, such a combustion control or advanced fuel development.

As discussed above the major issues which are being addressed by current generation of researchers are Detonation Initiation, Optimum Thrust Extraction, Reducing Cycle Losses and Proper Mixing and injection of mixture. We discussed about these problems and also had a brief review about various theoretical solution that scientists can look forward to.

6. ACKNOWLEDGEMENTS

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REFERENCES

[1] Kailasanath, K., "*Recent Developments in the Research on Pulse Detonation Engines*," AIAA Journal, Vol. 41, No. 2, 2003, pp. 145–159.

[2] Hoffmann, N., Ministry of Supply, Volkenrode Translation, 1940.

[3] Sudip Bhattrai, Hao Tang, "*Comparative performance analysis of combined-cycle pulse detonation turbofan engines*" Propulsion and Power Research 2013;2(3):214–224.

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

[5] M. Cooper, S. Jackson, J. E. Shepherd, "*Effect of Deflagration-to-Detonation Transition on Pulse Detonation Engine Impulse*". GALCIT Report FM00-3

[6] Sterling, J., Ghorbanian, K., Humphrey, J., and Sobota, T., "*Enhanced Combustion Pulsejet Engines for Mach 0 to 3 Applications*," AIAA Paper 96-2687, July 1996.

[7] Litchford, R. J., "*Development of a Gas-Fed Pulse Detonation Research Engine*," AIAA Paper 2001-3814, July 2001.

[8] D. You, F. Ham and P. Moin., "*Large-eddy simulation analysis of turbulent combustion in a gas turbine engine combustor,*" Center for Turbulence Research Annual Research Briefs 2008 Pg 219.

[9] John Hynes., "*Turbulence Effects on Combustion in Spark Ignition Engines*," Dept. Mechanical Engg. University of Leeds, 1986.

[10] Kentfield JAC (2002), "*Fundamentals of Idealized Airbreathing Pulse-Detonation Engines*," J Propulsion Power 18(1):77–83.

[11] Eidelman S, Yang X, (1998) "*Analysis of the Pulse Detonation Engine Efficiency*," AIAA Paper 98–3877

[12] Brophy, C. M., Werner, L. S., and Sinibaldi, J. O., "*Performance Characterization of a Valveless Pulse Detonation Engine*," AIAA Paper 2003-1344, Jan. 2003.

[13] Piton, D., Prigent, A., Serre, L., and Monjaret, C., "*Performance of a Valveless Airbreathing Pulse Detonation Engine*," AIAA Paper 2004-3749, July 2004

[14] Lu, F.K., Awasthi, M. and Joshi, D.D., "*Influence of Unsteadiness on Thrust Measurements of Pulse Detonation Engines*," AIAA Paper 2010-1214, 2010.

[15] E. Wintenberger, J.M. Austin, M. Cooper, S. Jackson, and J.E. Shepherd, "*Impulse of a Single-Pulse Detonation Tube*" Graduate Aeronautical Laboratories, GALCIT Report FM 00-8,