PULSE DETONATION ENGINE TECHNOLOGY: AN OVERVIEW

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ABSTRACT

Pulse detonation is a propulsion technology that involves detonation of fuel to produce thrust more efficiently than current engine systems. By library research and an interview with Dr. Roger Reed of the Metals and Materials Engineering Department of the University of British Columbia, it is shown that Pulse Detonation Engine (PDE) technology is more efficient than current engine types by virtue of its mechanical simplicity and thermodynamic efficiency. As the PDE produces a higher specific thrust than comparable ramjet engines at speeds of up to approximately Mach 2.3, it is suitable for use as part of a multi-stage propulsion system. The PDE can provide static thrust for a ramjet or scramjet engine, or operate in combination with turbofan systems. As such, it sees potential applications in many sectors of the aerospace, aeronautic, and military industries. However, there remain engineering challenges that must be overcome before the PDE can see practical use. Current methods for initiating the detonation process need refinement. To this end, both Pratt & Whitney and General Electric have developed different processes to accomplish this. Also, current materials used in jet engines, such as Nickel-based super-alloys, are inadequate to withstand the extreme heat and pressure generated by the detonation cycle. Therefore, new materials must be developed for this purpose.

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GLOSSARY

Aurora
A secret aircraft capable of travelling at speeds of Mach 6. Developed in the early 80's, however, only rumoured to exist.

Deflagration
The relatively gentle process of burning rapidly with flames.

Detonation
A sudden and violent explosion. The shockwave produced travels at supersonic speeds.

Low-bypass
Bypass is the term used to refer to air that is drawn into a jet engine, but does not enter the combustion chamber. Hence, low-bypass is an engine where the majority of the air enters the combustion chamber.

Mach
A ratio between the speed of sound in a medium and an object's speed. Mach 5 is five times the speed of sound.

Normal Stress
Refers to the stresses perpendicular to the plane being considered.

NOx
Term used to refer to Nitrogen Oxides produced by the combustion of hydrocarbons. NOx gases are considered to be greenhouse gases.

Ramjet
Type of jet engine that relies on an aircraft's speed to compress the needed air. They do not function at speeds slower than half the speed of sound.

Scramjet	Acronym for Supersonic Combustion Ramjet. Attains higher speeds than a ramjet. The combustion of the air and fuel mixture occurs at supersonic speeds.
Shockwave	A strong pressure wave. Thin disturbance waves are created and a fluid medium does not have to time react to them.
Specific Thrust	A measure of thrust per unit mass of air that flows through the engine. As it is therefore independent of mass, it is used to comparatively examine efficiency of engines of different sizes. An engine with higher specific thrust is more efficient.
Specific Fuel Consumption	A measure of fuel consumption per unit thrust. As it is therefore independent of thrust, it is used to compare efficiencies of engines that produce different amounts of thrust. An engine with lower specific fuel consumption is more efficient.
Stratified reaction	Describes a process where a fuel is combusted to reach the higher combustion temperature of a new fuel. This eventually leads to the detonation of the primary fuel.
Subsonic	Slower than the speed of sound (approx. 343m/s at sea level).
Supersonic	Faster than the speed of sound.
Tantalum	Element: Transition Metal. Atomic number 73 on the periodic table. Symbol: Ta.

Temperature Ratio	A comparison of temperature into the engine versus exhaust temperature. For aviation, this measure is approximately proportional to the speed of travel (ie Mach number).
Volatile	A volatile substance will explode more readily than a non-volatile substance.
Yield Strength	Stress level where the material no longer deforms elastically.
Yielding	Defined as the moment when a material deforms greatly for a relatively small increase in load. This occurs at the stress value called the yield point

1.0 Introduction

Imagine aircraft crossing continents and oceans at higher speeds and efficiencies. Imagine spacecraft launching with higher safety factors and lower costs. Imagine military craft operating in many flight conditions with increased performance. This is the potential for Pulse Detonation Engine (PDE) technology; it has the capability to revolutionize the aviation industry.

As PDEs are an extension of pulse-jet engines, they share many similarities. However, there is one important difference between them: PDEs detonate, rather than deflagrate, their fuel. Based on library research and an interview with Dr. Roger Reed (Metals and Materials Engineering, UBC), this report provides an overview of issues associated with air-breathing PDE technology.

PDEs are currently not in production, although research has been ongoing for several years and systems should be put to use in the near future. This report provides an introduction to the principle of pulse detonation propulsion and describes its advantages over current technology. Additionally, this report presents potential practical applications for the PDE, and discusses engineering problems that must be overcome.

2.0 Description of Pulse Detonation Technology

The main objective of pulse detonation research is to develop an efficient engine that is primarily used for high-speeds (potentially Mach* 5), as well as high-altitudes. The basic concept behind the technology is to detonate*, rather than deflagrate*, the fuel. The detonation of fuel results in immense pressure, which in turn is used as thrust.

2.1. The Beginnings

An exact history of pulse detonation technology is not easily determined. The history is unclear for reasons such as the secrecy involved in research as this technology could prove to be very profitable. What is known is that the technology is derived from pulse jet engines, and many organizations within the past five to ten years have produced test-bed engines. No engines have currently been put into production (Wikipedia 2004). However, some people disagree and believe the military used pulse detonation in the speculated Aurora* aircraft as early as 1980. The existence of this aircraft is in question, and therefore it is not possible to conclude the type of propulsion used.

2.2. Classifications

Pulse detonation engines (PDEs) can be classified in numerous ways. The type of fuel used, whether it is air breathing, or the number of detonation chambers, for example, are all ways in which the engines can be classified. Three broad categories can be established: Pure, combined-cycle and hybrid. Pure PDEs, as the name implies, rely only on a PDE, consisting of detonation tubes, an inlet, and a nozzle. Combined-cycle engines use different cycles at different speed ranges. These cycles include those of the PDE as well as a ramjet* or scramjet* flowpath among others. Hybrid engines are a combination of a PDE and turbofan or turbojet engines (NASA Glenn Research Center 2004, 3rd paragraph).

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* This and all subsequent words followed by an asterix are defined in the Glossary, pp. vi-vii.

2.3. Description

Before describing the wave cycle of a PDE, it is beneficial to understand the difference between detonation and deflagration.

2.3.1. Detonation Versus Deflagration

Deflagration is the relatively gentle process of burning fuel rapidly with flames. One of the main characteristics of deflagration is that the flame travels at subsonic* speeds. Detonation, on the other hand, can be thought of as a violent reaction that travels at supersonic* speeds. Detonation produces a much higher amount of pressure compared to deflagration (Aardvark, Pulse Detonation Engines 2004).

2.3.2. Wave Cycle

The wave cycle of a PDE can be broken down into certain stages (Figure 1). In the first stage of the cycle, air and fuel are drawn in through individual inlets. Once the two have been combined to create a flammable mixture, the combination is passed to the front of the detonation chamber, where it is then detonated. Upon detonation, the pressure of the mixture increases tremendously, which creates a shockwave* that travels the length of the chamber. There is no need for a series of shutters within the chamber, as in pulse jet engines, to ensure the explosion moves toward the rear; the shockwave instead serves the purpose of the shutters. When the shock wave reaches the end of the chamber all of the combustion products are discharged at once. As soon as the products exit, the pressure inside the chamber drops suddenly resulting in air entering its inlet (Wikipedia 2004). The cycle is then repeated up to hundreds of times a second. Figure 2 clearly shows the inlets as well as other significant features of a pulse detonation engine.
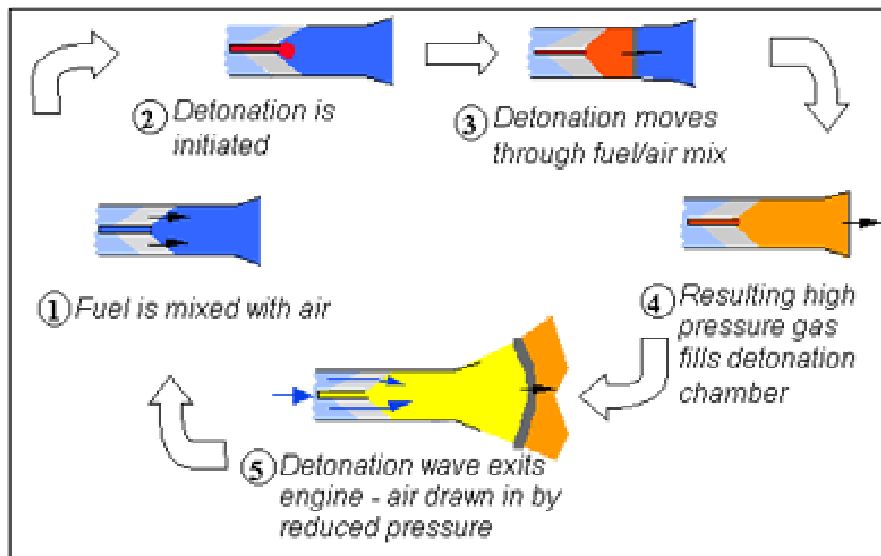
PDE Wave Cycle

Figure 1: A PDE Wave Cycle
Source: NASA Glenn Research Center, Pulse detonation engine technology project. (2004, January) Retrieved October 28, 2004 from NASA's Glen Research Center's Web site
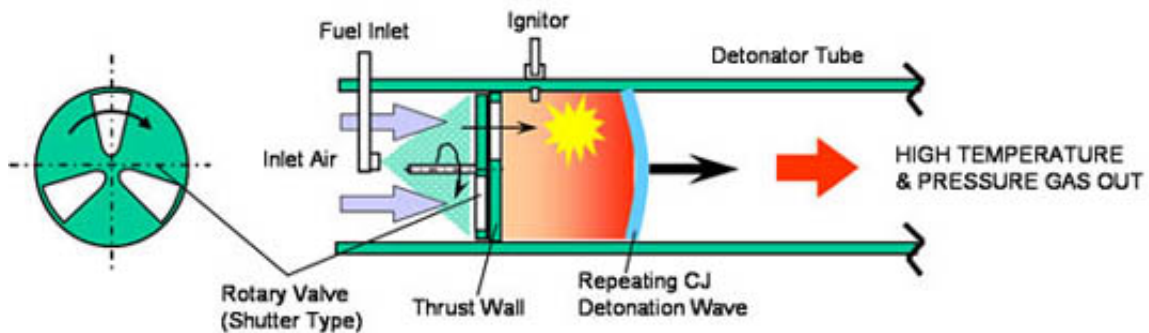<http://www.grc.nasa.gov/WWW/AERO/base/pdet.htm>

Figure 2: Configuration of a Typical PDE, Highlighting Major Features
Source: UCLA Combustion Research Laboratory, Pulse Detonation Wave Engine Simulation. Retrieved November 2, 2004 from UCLA's Combustion Research Laboratory Propulsion Projects Web Site
< http://www.seas.ucla.edu/combustion/projects/pulsed_detonation_wave.html>

3.0 Advantages of Pulse Detonation Propulsion

Pulse detonation engines (PDE's) exhibit several performance advantages in comparison with current steady-deflagration jets. The inherent mechanical design simplicity of the PDE results in smaller packaging volumes and lower part counts, aiding in integration and maintenance. The thermodynamic efficiency of the pulse detonation cycle results in higher theoretical performance across a wide speed range.

3.4. Mechanical Design Simplicity

Despite the apparent difficulties regarding the design of the PDE, its underlying mechanical principle is simple. Since the nature of the detonation process substantially increases the pressure within the detonation tube, fuel does not have to be injected at the high pressures that are necessary for significant thrust with a conventional engine. This eliminates the necessity for robust fuel injection pumps (Ebrahimi 2003). Additionally, this pressure compresses the intake air, thus mitigating the need for compressors, turbines or other heavy components typical of current liquid-fuelled engine types. Indeed, the PDE was specifically designed to avoid the mechanical complexity of spinning compressors or other rotating machinery in its air-flow path (Povinelli 2002). With the absence of a separate compression stage and the consolidation of the other stages of the detonation cycle into a single component, the PDE generally demonstrates a lower part count than other engine types (Mawid et al. 2003; Ebrahimi 2003; Povinelli 2002).

The PDE's mechanical simplicity offers many benefits to propulsion systems. The lower part count makes for simpler maintenance procedures. It also contributes to an overall lighter engine, improving the thrust-to-mass ratio of equivalent engine systems (Coleman 2004; Mawid et al. 2003). The simplicity as well as the number of the parts involved will decrease the cost of PDE propulsion systems (Ebrahimi 2003). It is clear that the PDE will therefore prove useful in propulsion systems when its engineering challenges – outlined in Section Five of this document – are surmounted.

3.5. Thermodynamic Efficiency

The thermodynamic efficiency of the pulse detonation process results in higher theoretical performance of the PDE across a wide range of flight conditions. Under ideal situations, the PDE has a theoretical performance advantage in both specific thrust and fuel consumption over conventional jet engines from the speed range of Mach 0-5. This is attributed to the near-constant-volume nature of the pulse detonation thermodynamic process (Coleman 2004). Figure 3 shows the theoretical thrust advantage of the PDE employed in a hybrid configuration with a turbofan engine, as opposed to the standard afterburner assembly.

Figure 3: Thrust Comparison of PDE and Conventional Turbofan
Source: Mawid, M.A. et al. (2003). Application of pulse detonation combustion to turbofan engines. Journal of Engineering for Gas Turbines and Power 125(1). 270-283.

As illustrated, the specific thrust* of the hypothetical hybrid PDE is considerably higher than that of the combustion cycle. However, Povinelli in Figure 4 shows that for non-ideal environmental conditions, the PDE exhibits a substantial performance drop-off at a temperature ratio roughly corresponding to Mach 2.3.

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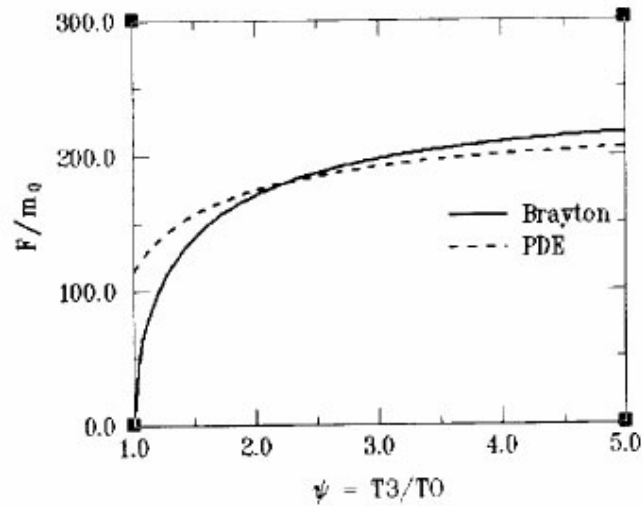
Figure 4: Specific Thrust Versus Temperature Ratio, Brayton (ramjet) and PDE cycles
Source: Povinelli, L. A. (2002, September/October). Pulse detonation engines for high-speed flight.
Prepared for the 11th American Institute of Aeronautics and Astronautics and the Association Aeronautique
et Astronautique de France International Conference, Space Planes and Hypersonic Systems and
Technologies, Orleans, France.
Retrieved October 29, 2004 from <http://gltrs.grc.nasa.gov/reports/2002/TM-2002-211908.pdf>

In addition to a performance advantage in low- to mid- speed ranges over conventional engines, the PDE also exhibits superior fuel economy. The extreme temperatures of the PDE reduce the presence of unburned hydrocarbons in the detonation cycle. Also, the speed at which the entire detonation takes place makes the thermodynamic cycle nearly constant-volume, improving fuel efficiency (Mawid et al. 2003). Figure 5 illustrates the results of these factors as they relate to the specific fuel consumption* of the theoretical hybrid turbofan PDE. Even for modest frequencies of detonation, the specific fuel consumption of a PDE system is shown to be substantially lower than that of a conventional equivalent.
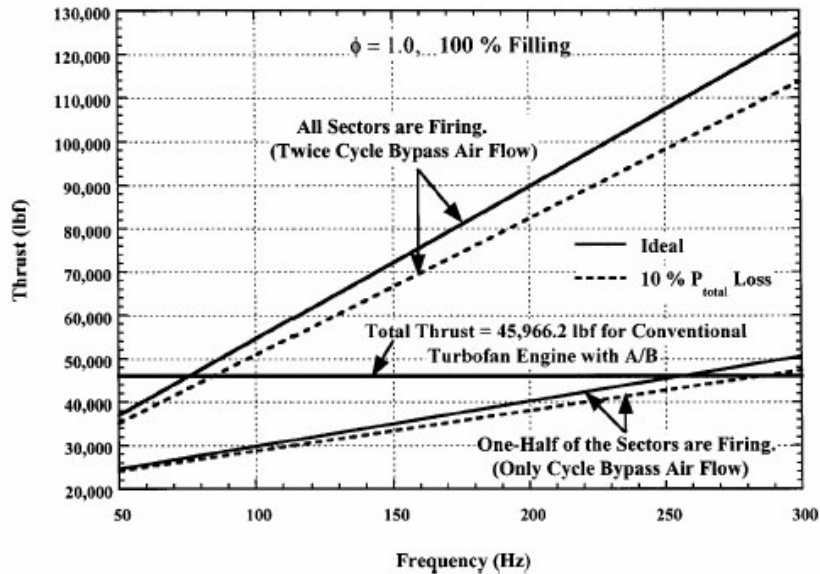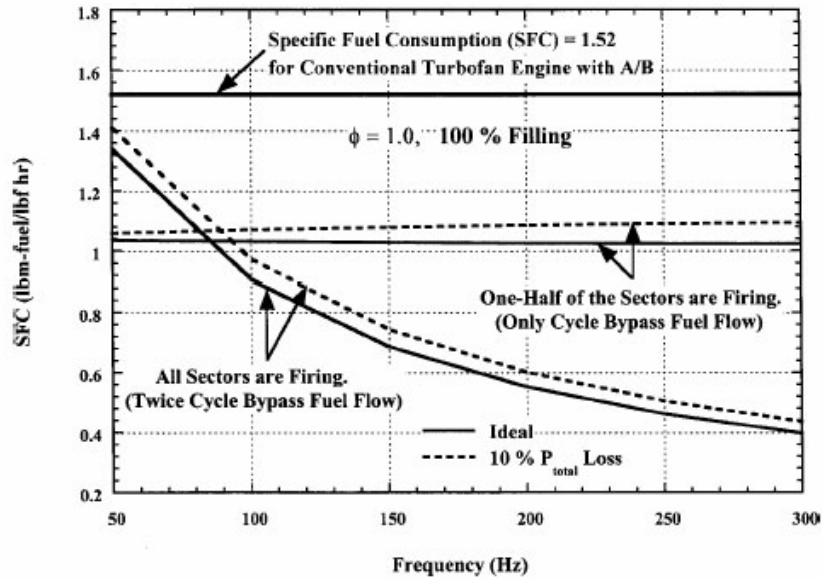
Figure 5: Specific Fuel Consumption Comparison, Conventional Turbofan and PDE
Source: Mawid, M.A. et al. (2003). Application of pulse detonation combustion to turbofan engines.
Journal of Engineering for Gas Turbines and Power 125(1). 270-283.

The above results show that while the performance of the pure PDE would be merely comparable to a conventional constant-cycle combustion engine, it is well-suited to an hybrid system where the PDE would be used in low- to mid-Mach number flight while a high-compression ramjet or scramjet would then begin operation (Povinelli, Anderberg and Lee 2001). More information on the potential applications of PDE technology can be found in Section Four of this document.

4.0 Applications of Pulse Detonation Propulsion

Pulse detonation technology has the potential to revolutionize both in-atmosphere and space flight. Having an engine capable of running efficiently at Mach 5 will not only allow for faster, more efficient intercontinental travel, but will also change the way spacecrafts are launched.

4.4. Applications to In-Atmosphere Flight

This section discusses the application of pure, combined-cycle and hybrid pulse detonation engines to continental and inter-continental flight.

4.4.1.   Hybrid Pulse Detonation

Pulse detonation engines are well-suited for combination with turbofan and turbojet engines. This hybrid combination can be applied not only to produce faster aircraft, but also to make them more efficient and environmentally friendly.

In a conventional turbofan engine, combustion is used to turn a large fan, which drives air into and around the combustion chamber. The air travelling around the chamber mixes with the exhaust from the combustion chamber to provide the thrust (Rolls-Royce 1986, 17). In a hybrid pulse detonation engine, the bypass air enters pulse detonation tubes that surround the standard combustion chamber (see Figure 6). The tubes are then cyclically detonated; one detonates while the others fill with air or are primed with fuel (Mawid et al. 2003, 271). This combination promises to require simpler engine mechanisms and yield higher thrust with lower fuel consumption (NASA Glenn Research Center 2004; General Electric 2004).
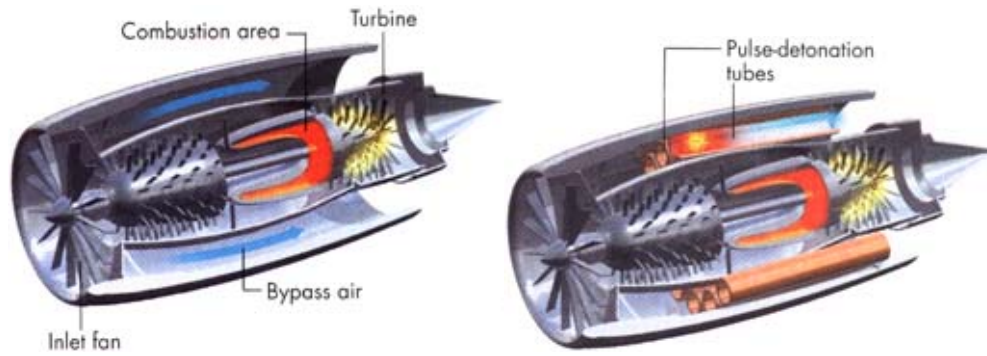
Figure 6: A Standard Turbofan Engine (left) Compared to a PDE Hybrid Turbofan (right)
Source: Carnett, J.B. 2003 How It Works: Pulse Detonation. *Popular Science*. 263:3, 53

Hybrid pulse detonation engines will allow commercial aircraft to be faster, more efficient, and more environmentally friendly. NASA is projecting that the inter-city travel time will reduce significantly by the year 2007, and inter-continental travel time will also reduce significantly by 2022, thanks to this technology. In addition, they suggest that NOx* emissions may decrease by up to 70% and 80% respectively in the same time periods (NASA Glenn Research Center 2004).

Similarly, hybrid PDEs can also be used in military applications. A large number of modern fighter jets employ afterburner-equipped low-bypass* turbofan or turbojet engines. In engines such as these, fuel is injected into the hot exhaust stream. The resulting combustion causes the exhaust gas to accelerate, and thus increase thrust. Although this process is an effective solution, it is not a fuel-efficient solution. Hybrid PDEs will deliver the same thrust with less fuel consumption (Benson 2004; Rolls Royce 1986, 170; Mawid et al. 2003, 270).

4.4.2. Pure Pulse Detonation

The applications of pure PDEs are primarily military, as they are light, easy to manufacture, and have higher performance around Mach 1 than current engine technologies (Marshall Space Flight Center). This makes them an ideal form of propulsion for missiles, unmanned vehicles, and other small-scale applications

(NASA Glenn Research Center 2004). The decrease in efficiency of PDEs at higher Mach numbers, the noise generated by them, and the advantages of using them in a hybrid combination, means that pure PDEs will likely not be used often for large-scale applications (Marshall Space Flight Center 200).

4.1.3   Combined Cycle Pulse Detonation

Combined cycle pulse detonation engines may provide the most exciting possibilities for aviation. Adding a PDE to the flow path of a ramjet or scramjet engine would make an engine capable of operating efficiently as high as Mach 5. As scramjet engines are still themselves under development, the full scope of this combination and its applications are difficult to evaluate. However, these engines would seem initially suitable for high-altitude, high-speed aircraft (Povinelli et al. 2001, 8).

4.5.   Applications to Space Flight

While air breathing pulse detonation engines would not be able to operate in space, they may be used to reduce the cost and complexity of launching spacecraft. As PDEs do not require heavy and expensive pumps, they offer a viable alternative to current rocket engines. The decreased weight, along with better fuel consumption, would significantly reduce the cost of launching spacecraft. Using pulse detonation in combination with other propulsion sources could potentially decrease the cost of launching payloads into space and the incidence of crew loss by a factor of 100 by the year 2025 (NASA Glenn Research Center 2004; Marshall Space Flight Center uncat.).

5.0 Problems Associated with Pulse Detonation Technology with Possible Solutions

Researchers wishing to implement Pulse Detonation Engine (PDE) technology have two main obstacles to overcome: Attaining successive detonations instead of deflagration cycles and engineering materials to withstand the immense pressures and thermal stresses caused by the blasts.

5.1. Deflagration to Detonation Transition (DDT)

The difference between conventional engines and PDEs is the use of detonation waves instead of deflagration to propel the vehicle forward. As such, the deflagration to detonation transition is necessary to attain the increased thermodynamic efficiency and other benefits of pulse detonation engines. The competing methods to control the DDT are through either mechanical or aerodynamic valving (valveless operation).

5.1.1. Mechanically Valved Operation

Pratt & Whitney began developing pulse detonation technologies in 1993. Their approach to overcome the deflagration to detonation transition (DDT) is through the valved intake method (Kelly 2003). This uses mechanical valves to supply the air-fuel mixture before detonation. These systems use a spark ignition to instigate the DDT. This allows engineers to regulate the fuel-flow to the detonation chambers (Roy et al. 2004). This also creates a near instant detonation, guaranteeing the thermodynamic efficiency and ensures detonation occurs, provided the spark has high enough energy to cause detonation instead of deflagration. To assist this, a more volatile* mixture may be injected near the spark whose explosion then triggers the main fuel in a stratified reaction* (Roy et al. 2004).

5.1.2. Aerodynamically Valved Operation

Another approach, taken by General Electric, relies on the pressure difference between the atmosphere and the engine cavity to supply the fuel-air mixture to the detonation chambers (Kelly 2003). This causes two main stages in the cycle: the entrance, when fuel is supplied, and the exit, after detonation. The fuel and air enter at lower pressures than during the detonation. By continually supplying the detonation tube with air and fuel, and ensuring that it only enters in between detonations, the timing of the explosions depends on the length and temperature of the tube. A buffer zone of previously detonated gases forms by cooling the exhaust, either naturally or with a coolant. This isolates the entering fuel mixture from the high temperatures that may cause premature detonation. This allows for proper mixing of the air and fuel (Roy et al. 2004). An electric spark then ignites the fuel, creating a deflagration which increases the temperature and pressure, leading to a detonation wave. This wave then propagates down the detonation tube propelling the vehicle forward and expelling the byproducts that form the buffer zone.

5.2. Physical Environment

PDEs work in an intense physical environment. Typical operating conditions for PDEs include temperature ranges of 227 - 1727 C and pressures from 0-20 MPa (He and Karagozian 2003). The high temperatures are needed to change the deflagration into a detonation wave (Ben-Dor et al. 2001). While the valving method influences the DDT, it has little effect on the immense heat and pressure associated with the technology.

The purpose of pulse detonation is to have many detonations propel the object forward. Research completed for 1m long detonation tubes operating at 1 atm pressure required detonation frequencies near 100Hz (one hundred detonations per second) (Roy et al. 2004). Other tests have peak pressures occurring every

14-18 μs. This means in three hours, the detonation tubes are loaded between 1 million and 771 million times. Table 1 shows operating temperatures and pressures for varying altitudes at a specific detonation velocity (Roy et al. 2004). Further calculations to show the unsuitability of current materials to endure PDE-related stresses can be found in Appendix A.

Mach Number	1		
Detonation Velocity: 1800m/s			
Height above Sea level (km)	0	3	10
Pressure(MPa)	5.33	3.94	1.78
Temperature(C)	1394	1558	1325

Mach Number	1.5		
Detonation Velocity: 1800m/s			
Height above Sea level (km)	0	3	10
Pressure(MPa)	8.31	6.18	2.83
Temperature(C)	1445	1425	1370

Mach Number	2		
Detonation Velocity: 1800m/s			
Height above Sea level (km)	0	3	10
Pressure(MPa)	12.25	9.04	4.12
Temperature(C)	1532	1500	1436

Table 1: Temperatures and Pressures of Various Operating Conditions
Source: Roy, G. D. et al. (2004). Pulse detonation propulsion: challenges, current status, and future perspective. Progress in Combustion and Energy Science, 30. pp. 624-634.

To make PDE technology a viable propulsion option, materials that can endure these conditions need developing. A possible solution involves specially created super-alloys, as these metals remain strong even at high temperatures. Super-alloys are currently used in the blades of some jet-engines because they remain strong enough to endure normal stresses* near 200 MPa at temperatures of 700°C.

For comparison, the Institut for Energiteknikk lists Grade 3 commercial pure titanium as having a yield strength* around 150MPa at temperatures near 400ºC (Seieresten 2000). The improved strength in super-alloys comes from the single-crystal structure of the metal, and the trace elements added. To improve the strength, tantalum*, aluminum, or titanium may be added to the nickel base. By adding a protective ceramic coating around the super-alloy, it can be placed in environments near 1300ºC., but this still falls several hundred degrees short of peak PDE operating temperatures. Until these criteria are met in an economical way, PDE technology will remain a theoretical possibility instead of a practical solution (Roger Reed, personal interview, 2004)

6.0 Conclusions

Pulse Detonation Engines (PDEs) can be broken into three categories: Pure, combined-cycle, and hybrid. However, the general principle of operation for each is identical: The fuel-air mixture is detonated in the engine cavity, rather than deflagrated. This violent thermodynamic process creates a pressure wave which compresses the fuel-air mixture of the following cycle; the process is repeated up to hundreds of times per second. The PDE in general has important advantages over current propulsion systems. The PDE has an inherently simpler mechanical design and a higher thermodynamic efficiency. As such, it is shown that the PDE is more efficient, in both specific thrust and specific fuel consumption, than current ramjet systems at speeds of up to approximately Mach 2.3. This performance advantage makes the PDE an excellent choice for static thrust up to mid- Mach numbers, where a ramjet or scramjet could begin operation in a multi-stage propulsion system. Therefore, the PDE has applications to many aerospace industries: Quick and efficient intercontinental travel, safe and cost-effective spacecraft launch, and effective military operation. However, before this occurs, certain engineering challenges must be overcome. The issues of transforming deflagration into detonation and developing materials able to withstand the intense heat and pressure must be resolved. Pratt & Whitney and General Electric have developed solutions to the deflagration-to-detonation problem. However, the engineering of new materials to endure the intense physical environment of the detonation cavity is a problem that remains to be solved.

APPENDIX A: HOOP STRESS CALCULATION [††]
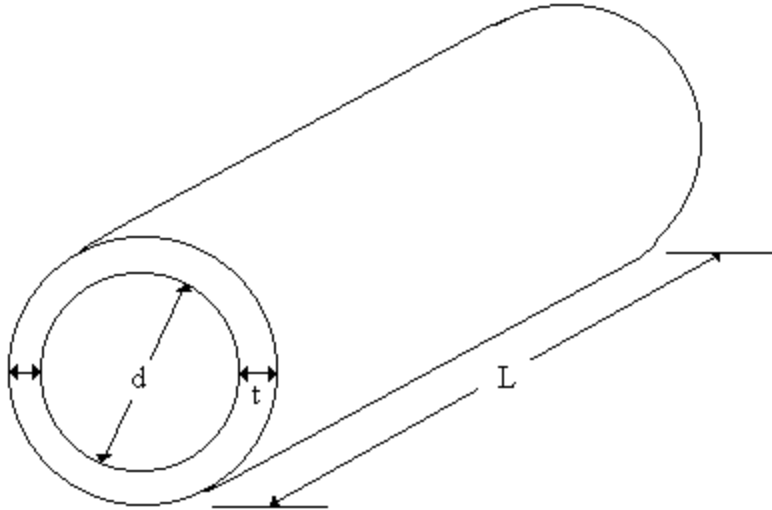
t is the wall thickness

d the inner diameter

L the length of the tube

p is the internal gauge pressure

v is the Poisson's ratio

Y is the elastic modulus of the given material

$$\sigma_t = \delta \cdot E = \alpha \cdot \Delta T \cdot t \cdot Y$$

$$\sigma_m = \frac{p \cdot d}{2 \cdot t} \cdot \left[1 - \frac{v}{2}\right]$$

$$\sigma_y = \sigma_m + \sigma_t = \frac{p \cdot d}{2 \cdot t} + \alpha \cdot \Delta T \cdot t \cdot Y$$

*This problem uses linear thermal expansion approximation and the thin-walled pressure-vessel approximation

We will consider a detonation tube made from quenched and tempered ASTM-A709 Grade 100 steel with Y = 200GPa and yield strength, σ_y = 690Mpa

The maximum hoop stress in the walls must not 690Mpa, the yield stress of the steel.

We will assume that the detonation tube is constrained such that it has no room for expansion. This will create large stresses induced by the thermal strain δ.

By first considering on the stress caused by 20MPa of gauge pressure, the minimum required thickness is

0.00370579m

Using this value to determine the corresponding thermal load yields

621 MPa

and exceeds our allowable hoop-stress by 100%, or 621 MPa.

Reducing the thickness of the cylindrical wall is required to bring down the thermal stress for some given temperature change, but this in turn reduces the strength of the wall.

The solution to this problem, will involve subtracting from the yield stress, the stress caused by the pressure, and ensuring that the induced thermal stress does not exceed maximum allowable stress by some factor of safety.

APPENDIX B: INTERVIEW WITH DR. ROGER REED

(Conducted October 5, 2004 and November 23, by Daniel Tillie)

- Temperature of combuster cans made of super alloys (SA) 500-700 C
- Ceramic coatings of cans engineered to have low thermal conductivity
    - Also have different coefficient of thermal expansion
    - Leads to internal tension of ceramic
        - $\alpha_{can} > \alpha_{cer}$ so can decreases more on the same ΔTemp compressing ceramic causing shear forces
- SA of jet engines Ni based with Al, W, Ti, Pt for strength stiffening
    - Bond coatings between SA and ceramic made of Al or Pt
        - Al coatings stabilize, Al_2O_3
    - Coatings prevent oxidation
    - How do they affect interface performance?
- Coatings required as NiO spoils due to expansion
    - NiO requires more volume thus put into compression while adhering to the metal. Eventually the build up creates a shear stress large enough to dislodge causing crumpling, folding, buckling, etc
- 1300 C operating temp of gas
- Average stresses 200-300MPa
- Yield strength of SA typically around 1000Mpa @ 700 C

Turbine Blades
- Single crystal
- Machined by electric discharge methods
- Experience high centripetal forces, spinning causes elongation
- Can take high temperatures

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