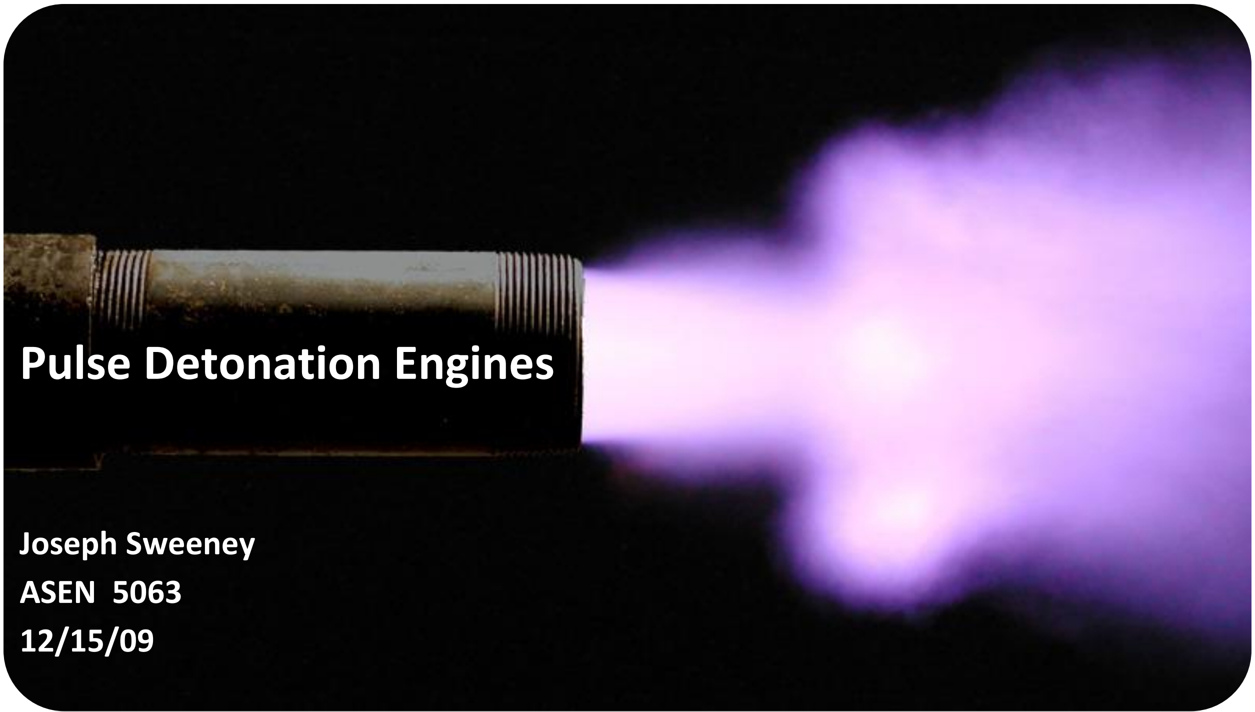

Pulse Detonation Engines

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What is a PDE?

The combustion process can be broken down into two main processes: deflagration and detonation. Most people are unaware of the difference between the two. Most of our daily interactions with combustion are deflagration processes: the engines in our car, gas stoves and bullet firings are all examples of deflagration processes. Most people do not think of a bullet firing as a deflagration process because it seems to happen so rapidly and produces a shock wave. However, the actual burning of the gunpowder occurs at a low, subsonic rate. It is simply the expansion of the gases that accelerates the bullet to supersonic speeds and produces the shock wave. This is the hallmark of deflagration: slow, subsonic combustion. Detonation, on the other hand, is the rapid, high-velocity, supersonic combustion of products.

Figure 1: Deflagration

Figure 2: Detonation

The goal of a PDE (Pulse Detonation Engine) is to harness the power of detonations to propel a vehicle forward. PDEs are being investigated because they can provide higher burn efficiencies over the entire Mach number range of gas turbine engines. The concept of a PDE is simple: inject fuel and oxidizer, detonate, expel gases, repeat. The “pulse” part of the name refers to the fact that PDEs would probably operate at a frequency of at least 50 Hz to achieve nearly-constant thrust.

History of Pulse Engines

Pulse engines (whether detonation or otherwise) are not a new concept. This section introduces some of the historic examples of fanciful (and sometimes real) vehicles that used pulse propulsion technologies.

Project Orion was designed to utilize small nuclear explosions against a pusher plate on the back of the vehicle. The specific impulse was estimated at 6,000 seconds, over 12 times the specific impulse of the space shuttle rocket engines. The theoretical maximum specific impulse for the vehicle was calculated to be as high as 100,000 seconds. The initial design of the vehicle called for a crew of over 200 and a takeoff weight of several thousand tons. Even this single-stage, low-tech version of the design was said to have been able to reach Mars and back in 4 weeks, much faster than NASA’s theoretical chemically-powered mission capability of 12 months. Shielding the crew from radiation, the pusher plate lifetime, pusher plate shock absorbers and fallout from the initial launch were found to be the largest problems the project faced. Some of the problems were solved, but the many other problems with controlling a nuclear explosion doomed the project.

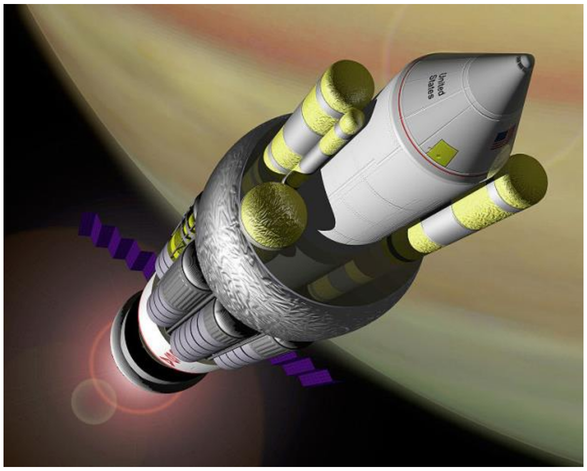

Figure 3: Project Orion

Another design employing pulse detonation concepts is the Medusa Project. This project was similar to the Orion design in the fact that it used exploding nuclear charges to propel the vehicle. The Medusa design, however, flipped a few concepts from the Orion design. Instead of ejecting a micro-nuclear charge out of the back of the vehicle, the Medusa design ejected the charge forward. The explosion was then captured in a parachute/sail structure to transfer the momentum to the vehicle. This design had the advantage that the support structure for the pusher/puller plate was in tension, in contrast to the Orion design. This allowed for a much lighter, smaller parachute structure. However, one of the main disadvantages to the Medusa design was that it dragged dragged the crew capsule through the radioactive debris instead of protecting the crew with a massive pusher plate.

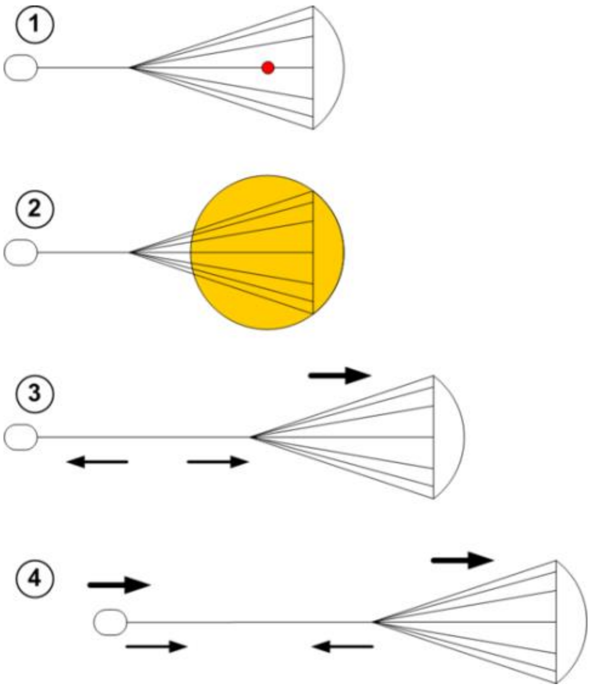

Figure 4: Project Medusa

One of the most secret vehicles rumored to have some form of pulse propulsion was the Aurora Project. The Aurora was rumored to be a hypersonic spy plane designed in the 1980s to 1990s. There were numerous accounts of people claiming to have seen or heard something like the Aurora during this time frame, but most accounts were treated the same as UFO sightings. One example that conspiracy theorists use is the "doughnuts-on-a-rope" picture at right, claiming that the PDE powering the aircraft produces the doughnuts with each detonation. This claim has been shown to not be accurate because such contrails would only be produced outside the Aurora's specified engine

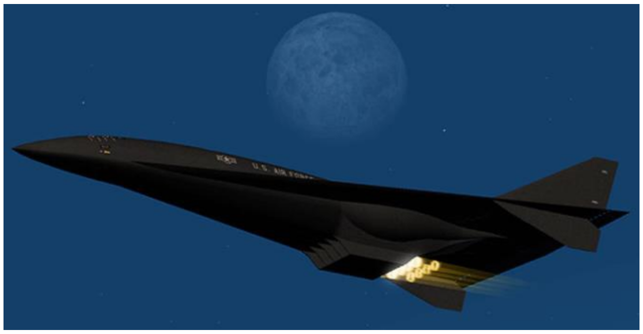

Figure 6: Speculated Aurora Design (X-Plane)

Figure 5: Doughnuts on a Rope

parameters. Also, calculations using an estimated distance between the doughnuts indicate a velocity of Mach 36, which is 4 times higher than the maximum velocity speculated for the Aurora.

Perhaps the most famous implementation of a pulse-propulsion system was the German V1 missile. While this weapon, widely recognized as the first cruise missile, did not operate as a pulse *detonation* engine, it did operate as a pulse *jet*. That is, it used deflagration rather than detonation. The actual powerplant for the missile is the small tube on top of the vehicle, as shown in the figure below. The missile was launched using a catapult or rocket boosters, but the pulse jet engine could propel the vehicle to speeds around 400 mph and carry a 2300-lb warhead. The concept of the pulse jet was very simple: a disk in the front of the tube had evenly spaced holes to allow air into the combustion chamber. An opening in the disk would allow oxygen to flow in and mix with the injected fuel. The following deflagration would increase the back pressure, causing the disk to rotate and the air flow to cease. Once the combustion had proceeded enough to lower the back pressure, the disk would rotate again and allow a new quantity of air in. This process was carried out at an estimated frequency around 45 Hz.

Figure 7: German V1 (Buzz Bomb)

Advantages/Applications of PDEs

PDEs have many advantages that warrant the careful examination of their performance and limits. The main advantages are listed below.

<u>Advantages of PDEs:</u>

- Higher thermal cycle efficiencies
- Higher specific impulse
- Static thrust
- Few moving parts
- High Mach limit

One of the main reasons that PDEs are an attractive propulsion system is their shared simplicity with other engine systems, namely ramjets and scramjets. Scramjets and ramjets are the mechanically simplest form of propulsion and hold much promise for the future of high-performance propulsion systems. However, these systems have one major drawback: zero static thrust. This is where the PDE shines. Because PDEs rely on detonation shocks to compress the working fluid rather than ram compression, they have thrust even at zero velocity. This major advantage, when coupled with the other benefits such as higher thermal efficiency and specific impulse, could make PDEs a very popular form of propulsion in the future.

One method of making ramjet and scramjets more practical is to use them in a combined-cycle (CC) approach. This approach has typically been thought of as a turbojet/ramjet/scramjet combination. This approach would allow for non-zero static thrust and still allow for operation above Mach 5. With the advancement of PDEs, a new CC system is possible. The new

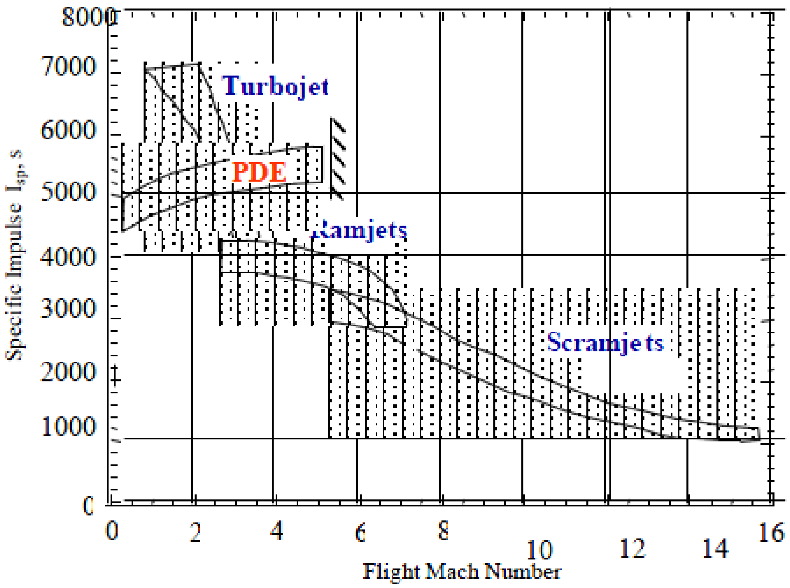

Figure 8: PDE Envelope

system would be a PDE/ramjet/scramjet combination. Since the PDE could operate very efficiently until around the Mach 2.5 range, this CC engine would allow for efficient ramjet takeover. This system would eliminate the heavy, complicated turbomachinery that would be rendered useless after the ramjet took over. The performance envelopes of all the air-breathing engine types are shown in the figure above.

Not all analysis of PDEs has been directed towards making vehicle-scale propulsions systems. Research has been done to investigate of the performance of micro PDE engines. Initial investigation into the field shows promise for applications of micro PDEs to satellite attitude control, micro power generation and more military applications like pre-detonation initiators for larger PDEs. Micro PDEs have the advantage of shorter relative purging, or blowdown, time. Shorter blowdown times allow for higher frequency operation. It is critical in these smaller PDEs that the cycle frequency is high to avoid thermal losses through the walls of the combustion chamber. An experimental setup (Kitano) is shown below with dimensions for an idea of scale.

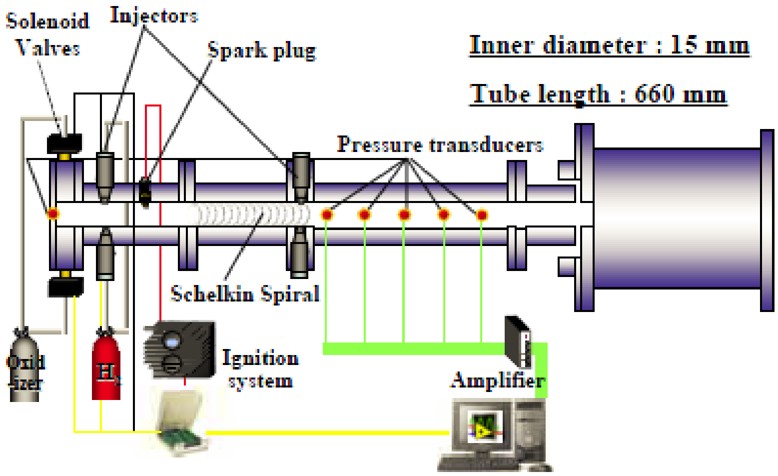

Figure 9: Micro PDE Experimental Setup

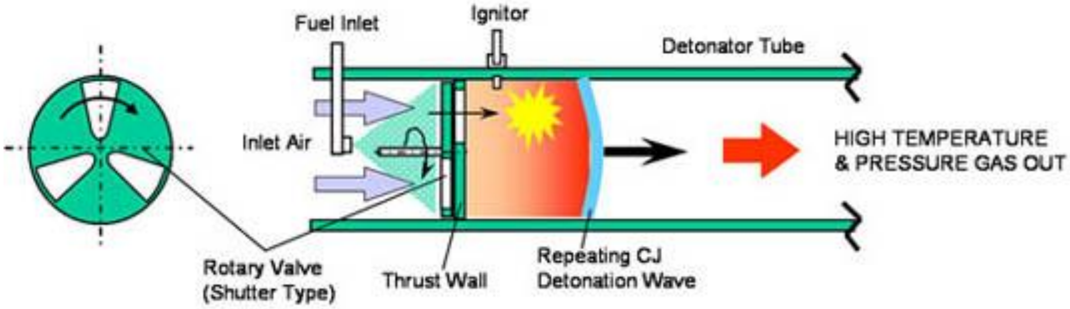

Figure 10: Basic PDE Setup

PDE Problems and Solutions

PDEs have a number of problems that must be explored in depth before a practical PDE can be built and flown. This section explores some of those problems and their solutions, if they exist.

<u>Problems of PDEs:</u> (Gabriel D. Roy)

- Liquid Fuel Detonation Physics
- Injection, Mixing and Initiation
- Inlet/Combustor/Nozzle Configuration
- Multi-tube/cycle Operation at High Frequency
- Diagnostics and Sensors
- Dynamics and Control
- Computer Simulations and Performance Predictions
- Noise
- Vibration

One of the most problematic issues with PDEs is the initiation and sustainment of detonations. Detonations can typically be initiated with high-energy sources, but reliable, low-energy ignition sources present a huge problem. The energy required to reliably initiate a detonation in hydrocarbon mixtures is far too high to implement in any sort of flight-worthy vehicle. The most popular way to combat this problem is through a phenomenon called detonation to detonation transition (DDT). Through this process, low energies can be input into the system to initiate deflagration. Using bodies in the flow to cause partial blockages in the flow path promotes the transition to detonation. The distance along the tube from the ignition point where the deflagration becomes detonation is known as the DDT length. This length could be 2.5 m for a 100 mm tube. Obviously, it is more desirable to have a shorter DDT length since this would allow for more efficient detonation combustion in a larger portion of the engine. The most popular way to shorten the DDT length is the Schelkin spiral. This is basically a helical blockage

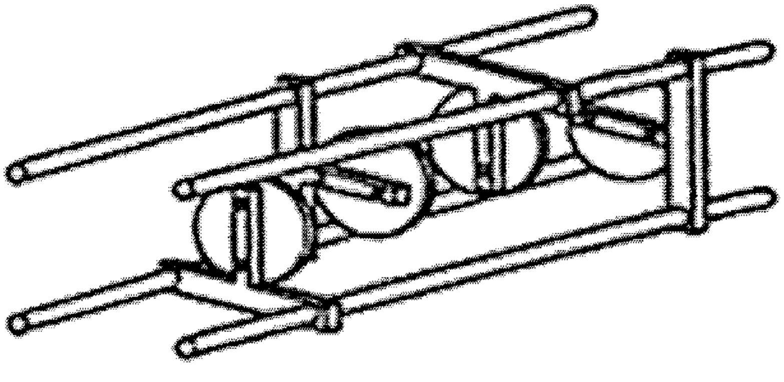

Figure 11 Example of Combustion Chamber Blockage

meant to accelerate the flame front. It has been found that the blockages in the flow must accelerate the flame to at least half the CJ speed for DDT. Without adequate mixing of fuel and oxidizer, the observed detonation velocities can be significantly lower than the predicted Chapman-Jouget detonation velocities. This can be fixed using turbulence-creating components, but these also lower thrust. One way to ensure adequate mixing is to premix the fuel and oxidizer before injection into the detonation chamber. Also, the time for DDT was found to decrease by 50% when running multicycle tests as opposed to single-shot tests. Another approach for initiating reliable detonation is the use of additives in the combustion chamber. Ethylene-oxygen mixtures can significantly decrease the DDT length and make detonations more reliable, but they have the drawback of requiring vehicles to carry extra tanks on board. The final popular method of encouraging detonation is the use of area changes in the combustion chamber. This solution uses the same principle that the Schelkin spiral and other such methods employ, but uses the actual geometry of the combustion chamber, rather than blockages in the chamber, to promote DDT. Some of these geometries can be seen in the figures below.

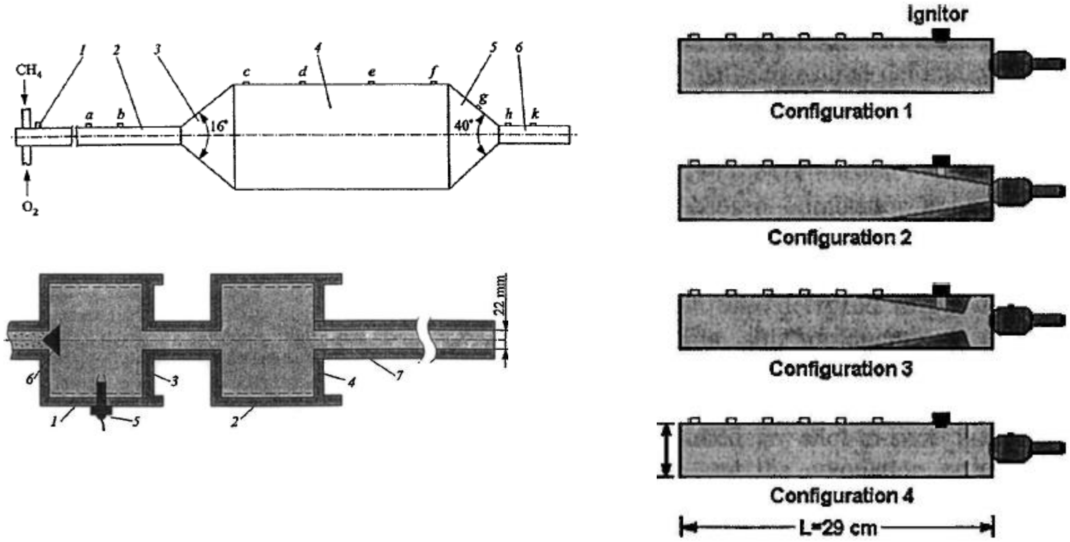

Figure 12: Variable Geometry Combustion Chambers

In most experiments involving PDEs, a gaseous fuel is used. For practical PDEs, the use of liquid fuels will be necessary for mass and aerodynamic requirements. Many studies have been conducted to try correlate injection physics and the resulting detonations. As would be expected, the more vaporized a fuel is, the better its ability to create a substantial reaction. One way to achieve enough vaporization of the fuel is to preheat the fuel before it s reaches the atomizers. For the combination of JP-10/air, a temperature at the injector of 425 K would be necessary to completely vaporize the fuel.

Beginning to integrate PDEs into a vehicle airframe also presents significant challenges. The first of these is the inlet. Inlets are inherently suited for steady flow while PDEs are, by nature, unsteady devices. There is some fear that the pulsing of the engine could produce enough back pressure or other phenomena to cause the inlet to unstart or disrupt the shock formation on the vehicle. There is some hope in the fact that using a multi-tube, high-frequency PDE system would create an almost steady thrust level. Another piece of technology that will be necessary for integrating PDEs is the ejector. The ejectors are basically fancy nozzles. They are coaxial ducts that control the entrainment of the engine exhaust and the surrounding flow. Ejectors are commonly used in steady-flow gas turbine engines, but they have not been widely used in unsteady flows. Preliminary research indicates that unsteady primary flows such as those at the exit of PDEs detonation tubes provide more efficient entrainment of the surrounding flow. This is thought to be due to the fact that the unsteady ejector entrainment occurs through inviscid mixing, while steady flow entrainment relies on viscous shear mixing.

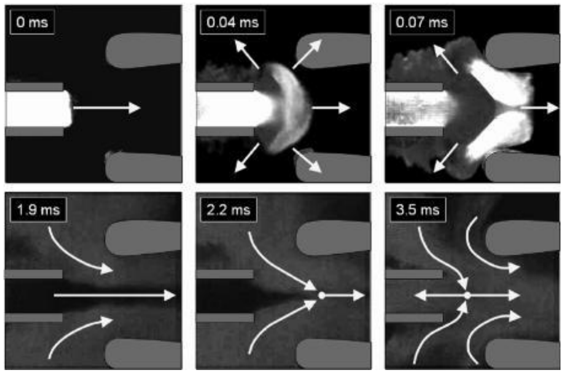

Figure 13: Ejector high-speed flame luminosity imaging

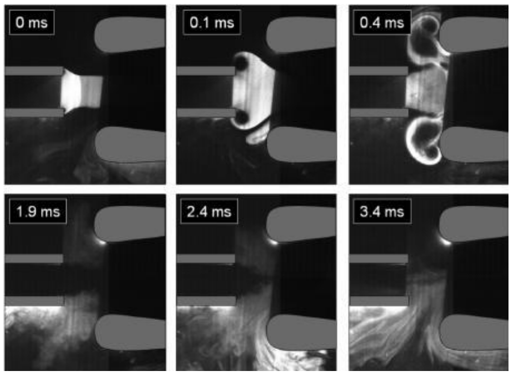

Figure 14: Ejector particle flow visualizations

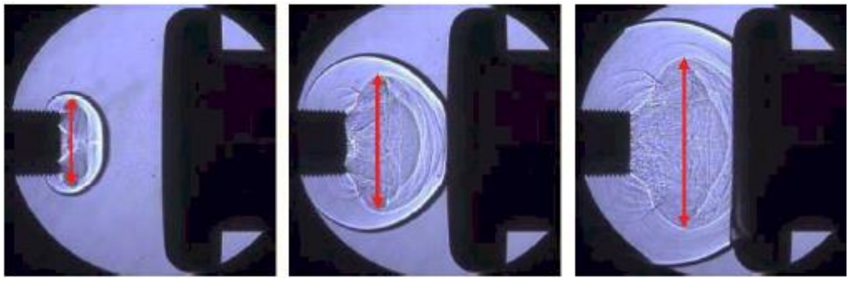

Figure 15: Interaction of PDE with Ejector

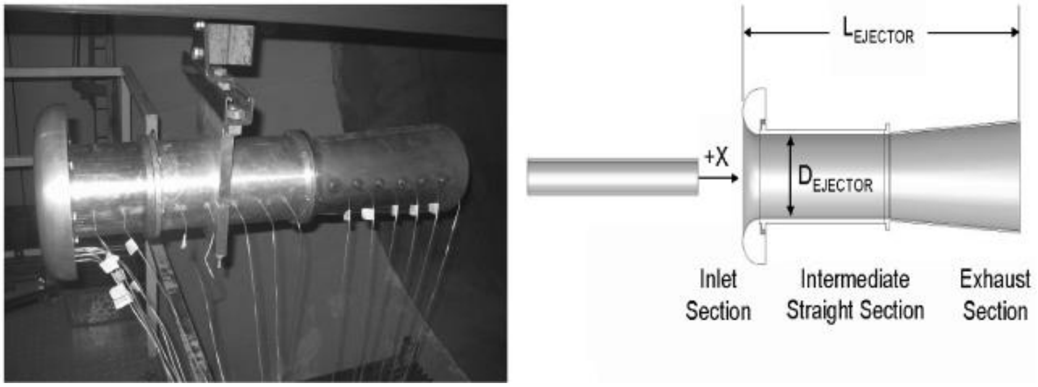

Figure 16: PDE Ejector Setup

The main aspect of PDEs that may prevent them from competing with conventional gas turbine engines is the increased noise from the exhaust since detonation is an inherently violent and loud process. Recent experiments (Kailasanath) using a PDE with a cycle frequency of 20 Hz resulted in noise levels from 100 – 122 dB from a range of 2.89 meters. Another experiment indicated an SPL of 147 – 159 dB at a range of 13 inches. The experiment did find, however, that much of the energy from the sound was at very high frequencies (above human hearing level) and above frequencies that were of structural concern. As would be expected, the SPL dropped rapidly with distance from the exit. However, noise mitigation techniques were not very effective at reducing noise levels. The physical mechanisms of noise generated from PDEs are not very well understood at this point because it stems from shock effects and jet noise. Adding to the complexity of the problem is that the flow velocity varies from subsonic to supersonic speeds with each cycle.

Military Applications

As would be expected with any new technology of this sort, there is great military interest. With the current state of development of PDEs, it is speculated that in the near future they will be limited to cheap missiles, UAV and UCAV (Falempin). The technology is more currently suited to missile applications because the use of PDEs in missiles eliminates two major problems: life of the system and noise. A missile is obviously only supposed to last for a short period of time as it flies to its target, and with the missiles probably operating at a high Mach number, and hence a high altitude, noise would not be a consideration. The second phase of PDEs that many see in the military is the application to fighter aircraft afterburners. By replacing the very inefficient dumping of fuel into the exhaust of the engine with efficient, powerful detonation waves, the thrust and efficiency of the afterburner could be significantly improved. The risk and drawbacks in the afterburner section are mitigated by the fact that afterburners only operate about 5% of the time during fighter operation and that detonation would take place in a simple tube rather than the turbomachinery itself. Many years from now, PDEs may be so well understood that the technology could replace the combustion chamber of turbojets, thereby significantly increasing existing turbojet performance.

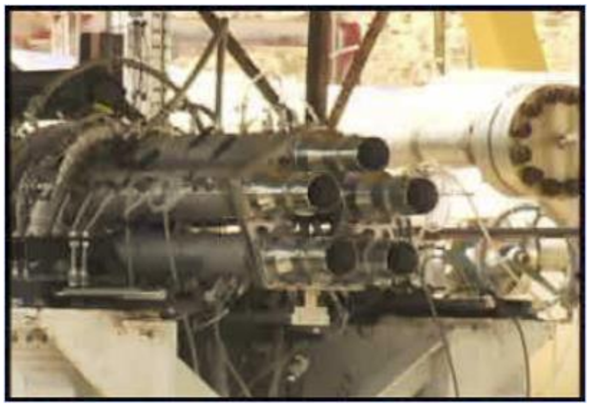

Figure 17: 5-Tube PDE Setup

Figure 18: 5-Tube PDE with Nozzle

For military applications, storability, availability and reliability are the main concerns for the fuel that will power PDEs. Also, hydrogen is not usable because of storage and safety concerns, especially for Navy use. These requirements are readily satisfied by liquid fuels. However, a liquid fuel needs to be found that satisfies the following requirements for practical purposes: no need for cryogenic storage, adequate hydrogen quantities at relatively low temperatures and high thermal capacity for cooling purposes. Even though some liquid fuels satisfy these requirements, some fuels would still be costly because of the need for cooling systems. A first look at a small-scale, cheap PDE-powered missile uses solid semi-propellant fuels to avoid the aforementioned problems. A general schematic of a PDE and an experimental PDE rocket are shown in the figures below.

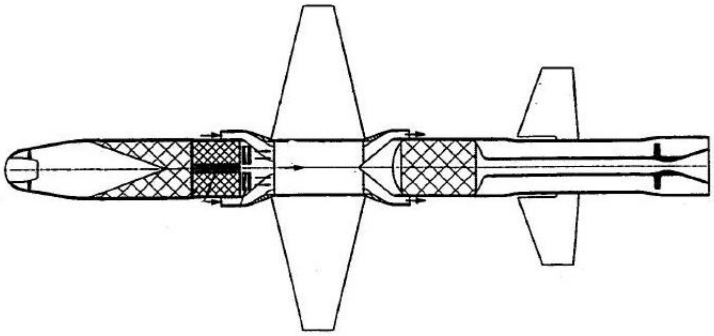

Figure 19: Proposed Baseline PDE Missile Design

Figure 20: Pulse Detonation Rocket, "TODOROKI"

Conclusions

Pulse detonation engines hold much promise for the field of aerospace engineering. While this technology may still be in infancy, it is already obvious that the technology can be applied to aircraft powerplants for nearly any range of Mach numbers, used for power generation, provide missile propulsion, augment satellite control systems or increase the performance of existing gas turbine propulsion systems. The combination of a PDE with a ramjet/scramjet engine may allow aircraft to reach a totally unexplored flight regime in the coming years. But before this technology can be fully exploited, many problems are left to overcome. Understanding the behavior of deflagration-to-detonation transition will be necessary to understand how these propulsion systems scale geometrically. Investigating the inlet/nozzle effects on performance will dictate the manner in which PDEs can be integrated into aircraft in the future. Without knowledge of the mixing process during multi-cycle PDE operation, designers will not be able to take advantage of high frequency PDE operation. Much work still needs to be done in this field, but the results of that work may revolutionize the propulsion industry.

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