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Propulsion from the Pulse Detonation of Solid Propellant Pellet-Projectiles

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Conventional solid propulsion is one of the oldest methods of propulsion that make use of deflagration phenomena rather than detonation to generate combustion gases. Proposed is a technology that makes use of detonation phenomena of solid propellants. This technology substantially departs from the conventional concepts and designs, and in doing so provides a system primarily developed for the purpose of providing a propulsion method that would have the advantages of both solid and liquid propulsion systems. The primary concept is that solid propellant pellets having a specific shape-profile is ejected in the form of projectiles having a certain velocity, interacts with a medium for initiation and the detonation of the solid propellant pellets takes place in flight. The velocity, the shape profile of the propellant pellets and the detonation process determines forward direction of the combustion gases evolved. The proposed technology has a specific application in space vehicle propulsion, and also in satellites where a propulsion system is required to reach correct orbit and carrying out its useful mission. Furthermore, variants of the proposed concept can be employed as in the case of detonation driven ramjets (dramjets) and detonation initiators for pulse detonation engines (PDEs).

I. Introduction

CONVENTIONAL solid propulsion is one of the oldest known propulsion technique to mankind in association with fireworks, fire arrows, cannons and guns. The invention of composite propellants and the technique of radial internal burning changed the view of solid propulsion as an art of black powder. The reliability and innate simplicity of solid propellant motors (SRM) make them still attractive for most practical applications. Typically the solid propellants are derivatives of explosives, where the propellant charge is stationary and combustion takes place by deflagration phenomena. Conversely, solid propulsion systems are inferior to liquid propulsion systems in thrust control and reuse of engine. But liquid propulsion rocket engines contain volatile, toxic, corrosive or cryogenic propellants. Hence the engine needs to be filled in short time before firing, thus requiring complicated and lengthy pre-firing preparations. In order to make solid propellant motors throttleable, many innovations were being considered that includes solid propellant in the form of particles or pellets were dropped into the combustion chamber and ignited. The solid propellant may be soaked in a fluid (which can be an oxidizer or liquid propellant) or transported by some means into the combustion chamber.[1,2] The real concern with such engines were in the feeding system, the feeding channel must be perfectly sealed in a very short time to prevent the combustion gases leaking through the seal and causing fire in the feeding system.

Combustion of propellants using detonation phenomena is an extremely efficient means of releasing the chemical energy content. The combustion process is subsonic in deflagration, whereas it is supersonic in detonation. The detonation process is several times faster than a deflagration process that leads to several advantages such as more compact and efficient propulsion systems. Efforts have been on for the past six decades, to harness the detonation potential of liquid and gaseous propellants.[3] Especially since the second half of 1980's there are renewed interests for developing pulse detonation engines (PDEs) using these propellants. The heat addition in PDE is thermodynamically closer to an isochoric process than the isobaric process in conventional propulsion systems. Theoretically, the thermodynamic efficiencies for isobaric process, isochoric process and detonation process are 27%, 47% and 49% respectively (in all cases, adiabatically compressed from 1 to 3 atm before heat addition and adiabatically expanded to 1 atm after heat addition).[4] Although the inherent nature of PDE is unsteady, transient pulse detonation process; the overall system can be stabilized by using a high frequency, multi-tube system. To date,

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PDEs based on gaseous mixtures have been more successful compared to multi phase mixtures involving liquid propellants due to the problems associated with injection, mixing and detonation initiation for these engines.

With all the efforts directed towards the development of propulsion techniques using detonation of gaseous and liquid propellants, no attempt was made to exploit the detonation potential of solid propellants, except using laboratory scale solid particulate / dust detonation systems[5] and during the initial phase of project *Orion*[6] wherein the early models used high explosive devices instead of nuclear devices. This paper presents a method of propulsion that uses detonation rather than deflagration for the combustion of solid propellants. The proposed concept[7] has certain advantages of liquid propulsion systems, such as thrust control and reuse of engine. Additionally, feasibility of the concept, solid propellant selection for pulse detonation and specific potential applications are discussed.

II. Concept of Pulse Detonation using Solid Propellant Pellet-Projectiles

Contrary to the wide use of deflagration phenomena in solid propellants for propulsion, proposed is a method of harnessing detonation phenomena in solid propellants. Typically, solid propellants or explosives have an available energy content of approximately 5 x 10^6 JKg^{-1}. When detonated over a period of few microseconds the power developed would be the order of 10^{11} to 10^{12} WKg^{-1}, which is enormous compared to a power output of 10^9 WKg^{-1} from deflagration. The principal concept is that solid propellant pellets having a specific shape-profile are ejected in the form of projectiles having a certain velocity (analogy to a bullet fired from a gun), interacts with a medium for initiation and the combustion of the solid propellant pellets takes place in flight. To attain this, the propulsion system[7] (Figure 1) consists of a storage chamber housing the propellant pellets, a pellet feeding system comprising of a feeding channel and feeding mechanism, a gun assembly to eject the propellant pellets at a certain velocity, a triggering mechanism to trigger the detonation of propellant pellets, a combustion chamber where detonation takes place, and an exhaust nozzle. In addition, it contains an auxiliary power system to power the feeding mechanism, gun assembly and triggering mechanism, and a control system that control the sequence and coordination of feeding mechanism, gun assembly and triggering mechanism.

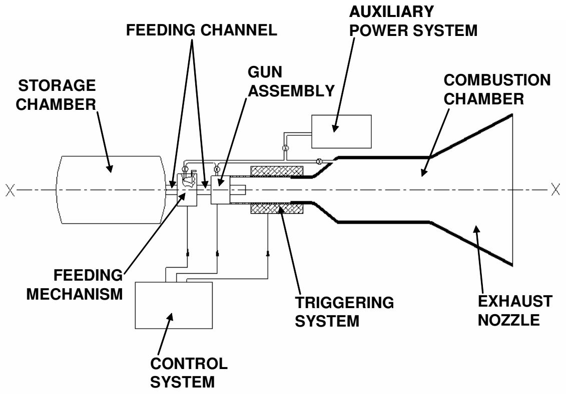

Figure 1. Schematic of the concept of pulse detonation using solid propellant pellet projectiles.

The storage chamber is essentially an enclosed space for storing the propellant pellets of specific shape profile that protects them from degrading or accidental detonation. The feeding system consists of a feeding channel and a feeding mechanism. The feeding mechanism drives the pellets from the storage chamber through the feeding channel into the gun assembly. The gun assembly may include an ejector mechanism and barrel. The ejector mechanism ejects the propellant pellets through the barrel at a certain velocity. The gun assembly may have more than one barrel for ejecting the propellant pellets in a particular sequence. The barrel gives direction to the propellant pellets ejected. The triggering system produces a medium that would create an ambience for the initiation of propellant pellet-projectiles. The thrust from the detonation of propellant pellets is generated from the combination of a combustion chamber and an exhaust nozzle. The combustion chamber is shielded on the inside with material that could withstand the heat, shock and high pressures of detonation of propellant pellets. The auxiliary power system is used for powering various systems within the propulsion system. These systems include pellet feeding mechanism, gun assembly, triggering system, and the various electrical and electronic systems that may be present in the proposed propulsion system for controlling the various engine components. As shown in figure 1, the auxiliary power system preferably includes piping for circulating tapped exhaust gases from the combustion chamber, control valves for controlling the flow of exhaust gases through the piping and small turbines for powering various systems within the propulsion system.

The general method of operation of the proposed propulsion system is described as follows. The propulsion system uses solid propellant pellets of a specific shape profile. The propellant pellets that are stored in the storage chamber are fed to the gun assembly through the feeding channel by the feeding mechanism. In the gun assembly, the ejector mechanism ejects the propellant pellets through the barrel at a certain velocity. The barrel gives direction to the propellant pellets ejected. The propellant pellet-projectiles emerging from the barrel interact with the medium generated by the triggering system, causing initiation of the propellant pellets. The initiation technique is pertinent to the type of solid propellant used, that includes initiation by heat, flash or flame, percussion or shock, and coherent light (laser). The use of laser is promising as highly laser-sensitive compositions are generally insensitive to friction, impact, or other initiation stimuli, thereby providing better safety.[8] The combustion of the propellant pellets takes place inside the combustion chamber. The detonation process creates large pressure increase in the combustion chamber that would result in an engine having very high thrust, provided the frequency of detonation is very high. Alternatively not including the triggering system, the initiation of the propellant pellet can occur by using a primer bonded to the propellant pellet, such that the primer would trigger the detonation process of the propellant pellet. The ignition of the primer can be made while exiting the gun assembly. The velocity, the shape profile of the propellant pellets and the detonation process determines forward direction of the combustion gases evolved. Finally the hot gases expand in the nozzle producing thrust for the engine. The existence of nozzle can likely improve the performance of the engine significantly, as has been reported with experiments on PDEs at high pressure ratios.[9] In general, the thrust produced can be varied by controlling the number of pellets ejected from a barrel in a time period and also by controlling the total number of pellets ejected at any particular instant in the case of multi-barrel gun assembly.

III. Feasibility Study of the Concept

Experiments with pulse detonation engines (PSEs) employing gaseous or liquid fuel and oxidizer have proven that pulse detonation is a practical method of producing propulsion. However, practical developments so far have been limited to experimental or laboratory based systems primarily due to the issues involved in the creation and sustenance of detonation rather than the detonation process itself. This section elucidates the feasibility of the proposed system based on a preliminary analysis and from the declassified information available on project *Orion*. An advanced analysis is beyond the scope of this paper due to complex nature of solid phase detonations that requires detailed study and modeling.

A. Preliminary Analysis

The initiation time varies between a few nanoseconds for typical explosives to a few milliseconds for typical solid propellants. The combustion time for detonation can vary from a few microseconds to a few hundredth of a millisecond for a propellant pellet of average size 10 mm. Accordingly, a total initiation and combustion time of 0.5 milliseconds with a propellant pellet velocity of 500 ms^{-1} may require the minimum combined length of triggering system and combustion chamber to be 0.25 m. Essentially, the size of the engine depends on the type and sensitivity of the solid propellant used. Considering that a propellant pellet is ejected every 5 milliseconds, the frequency of the above instance would be 200 Hz. Theoretically it is possible to go up to 2000 Hz with complete combustion, the onus abide with the capabilities of the feeding system and gun assembly. Furthermore, the overall system can be stabilized by using a multiple engine system.

B. Project Orion

Project *Orion*[6] was a classified project initiated by Advanced Research Projects Agency (formerly ARPA, at present DARPA) aimed in building an interplanetary spacecraft powered by nuclear bombs. The concept relies on ejecting slow-moving propellant (a nuclear bomb) away from the spacecraft, igniting the bomb, and then uses the external nuclear explosion to power the craft. To be precise, Orion uses pusher plates (circular-shaped disks connected to the craft by shock-absorbing mechanisms that transmits tolerable impulse to the craft) to propel the craft by means of detonation of fission bombs at a certain distance away from the craft. One of the reasons that made Orion attractive was the use of low yield nuclear bombs with relatively large amount of high explosives. During the initial phase of the project, reduced scale models were tested that used high explosives (non-nuclear) as propellants. The fact that small high explosive charges ejected and detonated in sequence were able to successfully propel the model craft substantiate the feasibility of the proposed concept. Furthermore, these charges were detonated outside the craft wherein only a portion of the power delivered was available. Nevertheless in the proposed concept almost all the detonative power available is utilized.

IV. Selection of Propellants

The detonation phenomena in solid propellants are primarily dependent on the chemical composition, propellant mass, grain structure, propellant initial temperature, degree of inhomogeneties, and a host of various other parameters. The selection of the solid propellants essentially depends on the type of application, for instance space application. Since most solid propellants and explosives contain fragments of fuel and oxidizer in their chemical composition, there is no clear cut boundary between them. Traditionally, the most common detonating solids are referred to as *high explosives*. In high explosives the pressure of reaction would be of the order of 3 x 10^5 bar, whereas for low explosives it would be less than 4 x 10^3 bar. The high explosives used for military purposes are trinitrotoluene (TNT), pentaerythritoltetranitrate (PETN), cyclotrimethylenetrinitramine (RDX), tetramethylenetetranitramine (HMX), and hexanitrostilbene (HNS) having high densities and detonation velocities of 7045, 7975, 8639, 9110 and 6800 ms^{-1} respectively.[8] Typically, mixtures of these explosives along with other materials are used, either to reduce the sensitivity or for complete combustion. Certain mixtures of TNT such as Amatol (20% TNT, 80% ammonium nitrate) and Ammonal (15% TNT, 65% ammonium nitrate, 17% aluminum, 3% charcoal) have low explosion temperature, can be used to minimize the thermal signature of exhaust such as in military applications.

In solids, if the reaction times are long the Chapman-Jouguet (C-J) condition can be reached before the termination of the reaction. This would result in non-ideal detonation, wherein the energy released outside the C-J condition will not contribute to detonation. In essence, there will be a tendency for a decrease in detonation velocity with increase in particle or grain size.[10] This suggests the use of nano-sized propellant-grains for ideal performance.[11,12]

V. Specific Potential Applications

A wide variety of applications can be proposed similar to PDEs, such as supersonic vehicles, cruise missiles, space vehicles / space crafts, unmanned air vehicles (UAVs), and afterburners for high performance aircrafts. Furthermore, variants of the proposed concept can be exploited as in the case of detonation driven ramjets (dramjets) and detonation initiators for PDEs.

A. Detonation Driven Ramjet Engine

Similar to PDE based detonation driven ramjets (dramjets)[4] or pulse detonation ramjet engines (PDRE)[13], there is a possibility of using the proposed concept as detonation driven ramjet engines. Performance analyses show that PDE has significant potential in low-speed (subsonic) performance over conventional ramjet engines.[13] The flow inside a dramjet has to be accelerated or decelerated to velocities slightly higher than or equal to the C-J detonation velocity for stabilization. The dramjets at speeds operating above Mach 6 depend on a wedge-shaped object (centerbody of the ramjet) for the stabilization of oblique detonation wave (ODW).[4] A similar approach can be taken for the proposed concept as well. Furthermore, the propulsion transforms to a steady-state operation as an oblique detonation wave engine ODWE, an operating mode equivalent to a scramjet.

B. Detonation Initiator for Liquid Propellant Pulse Detonation Engines

In air-breathing version of PDEs, usage of kerosene based liquid fuels such as JP-5, or JP-10 would have practical significance due to their high-energy density and their current acceptance in the aviation industry. However, these fuels are quite insensitive to direct detonation initiation and difficult to detonate in a reliable manner. Research is ongoing for the development of initiators that consist of a small auxiliary PDE using a mixture that is highly sensitive to detonation as a means to initiate the less sensitive mixture.[3,14] The highly sensitive mixture may be of the same fuel or another fuel with oxygen, which requires carrying onboard oxygen or oxygen generators for flight applications. In this context, the proposed concept can be used to initiate detonation with a transmission of detonation waves from an auxiliary engine using solid propellant pellet-projectiles to a main tube that contains the mixture of interest.

VI. Conclusion

Combustion using detonation phenomena is an extremely efficient means of releasing the chemical energy content of propellants. Experiments with pulse detonation engines (PSEs) employing gaseous or liquid fuel and oxidizer have proven that pulse detonation is a practical method of producing propulsion. However, practical developments so far have been limited to experimental or laboratory based systems primarily due to the issues involved in the creation and sustenance of detonation rather than the detonation process itself. A concept of propulsion using pulse detonation of solid propellant-projectiles has been presented. The proposed concept has certain advantages of liquid propulsion systems, such as thrust control and reuse of engine. Initial assessment shows that this concept is viable for various practical applications including space vehicle propulsion, dramjets and detonation initiators for PDEs.

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