IJESRT
INTERNATIONAL JOURNAL OF ENGINEERING SCIENCES & RESEARCH TECHNOLOGY

A STUDY ON ELECTRICALLY CONTROLLED SOLID PROPELLANTS

Rupesh Aggarwal *, Ishan K. Patel, Thirumalvalawan
* Teaching Assistant, Department of Aerospace, Amity University Haryana, India
Student, Deapartment of Aerospace, Amity University Haryana, India
Student, Deapartment of Aerospace, Amity University Haryana, India

ABSTRACT
Present Study focuses on the type of solid propellant whose burn process can be controlled electrically. The major disadvantage of solid propellant is once extinguish it can't be stopped which may lead any mis-happening to a disaster. When such propellant is fitted with electrodes, current & voltage are applied, it ignites and burns continuously until voltage is removed. Further it may be re-ignite accordingly. Conclusivly providing variable, controlled & required thrust.

KEYWORDS: Burn Control Propellant, Electrically Controlled solid propellant, Solid Propellant.

INTRODUCTION
Although solid rocket propellants have some advantages over liquid rocket propellant such as excellent characteristic storability and handling, easy transportation, higher energy density, simplicity and low cost. Besides, they have major disadvantages viz. deficiency in throttle-control and re-ignition of propellant once extinguished. Contrary, liquid propellants have good throttle controllability, and are re-ignitable at will. However they are highly toxic (NOX, ClF_5 & ClF_3) and require complex cryogenic storage systems (LOX/LH, FLOX/LH) to sustain their liquid state, otherwise liquid propellants are greatly unstable at higher temperature range.

Albeit solid propellants can be programmed to regulate thrust by employing various propellant grain geometry. This method holds no good for larger rocket motors, being limited up to small-scale rockets or amateur rockets. Current technology suggests more versatile mechanism – Electric Control of solid propellants, which is a subject of extensive research. In this method electric fields are exploited to regulate ignition and thus throttle of solid propellants. Another popular method for controlling chamber pressure and consequently the thrust, is pintle nozzle operation. These controllable solid propellant systems are emerging as adaptable propulsion system for commercial as well as research based applications.

In addition, two more methods seem promising[1]: (1) regulating burning rate of the propellant grain, (2) regulating the flame profile over internal surface of the grain. Amongst above mentioned methods, the latter seems more favourable since electrodes can be used to increase the flame spread by making the propellant one electrode which induces ionic winds over the surface of the grain.

DEVELOPMENT IN ELECTRICALLY CONTROLLED SOLID PROPELLANT (ESP)
ESP has its major implications in the emerging field of exotic rocket propellants since 1999 when DSSP (Digital Solid State Propulsion) company developed the first ECESP (Electrically Controlled Extinguishable Solid Propellant) under UAF SBIR funding[2]. This propellant was called "ASPEN", which demonstrated multiple ignitions and extinguishments and throttle control with variable Electric power input.

DSSP invented a new form of ESP known as High Performance Electric Propellant (HIPEP), which is impervious to spark and even bullet shock making them much safer to convey and operate over[3]. These HIPEPs are easily manufacturable and uses non-toxic or 'green' chemical compounds. Lately DSSP designed a micro-thruster consuming this green ESPs. This micro-thruster works in a method much analogous to Pulsed Plasma Thruster (PPT), which is traditional a category of Electric Propulsion System[4]. Due to the considerably small size, simpler integration and modest power requirement, these micro-thrusters are well applicable to smaller spacecraft and micro-satellites.

POSSIBILITY OF SUBSTITUTING CONVENTIONAL PPT-FUELS WITH HIPEP

PPT (Pulsed Plasma Thruster) is a magneto plasma dynamic (MPD) device works by exciting an insulator - solid propellant with high current discharge pulsating from one side of the grain to the other between a set of electrodes, ablating the propellant by heating and sequentially vaporizing and ionizing the exposed area of the propellant grain[5]. Afterwards, the plasma been produced is accelerated to high speed, typically in the range of 45-55 km/s by the aid of electromagnetic force generated by electric channels. These type of thrusters are employed for manoeuvring application such as station-keeping, orbit transfer, and attitude control[6][7][8][9].

Conventionally Teflon is used as a monopropellant fuel in PPT thrusters, which is electrically insulator. On the other hand, HIPEPs ought to be good conductors of electricity. Yet experiments were conducted to study the behaviour of these propellants. One such study was held by researchers at DSSP, who developed a micro-thruster exploiting HIPEP[10]. These micro-thrusters depicted in Fig.1 below, worked in a way much similar to that of typical PPTs.

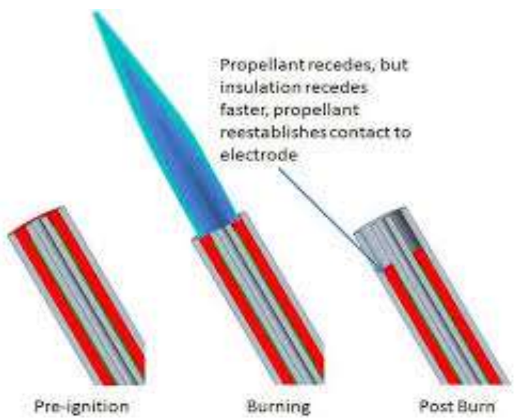

Fig 1: Operation of HIPEP micro-thrusters developed by DSSP

Experimental results indicated that HIPEP based micro-thrusters render comparatively lower electron density after considerably greater ablation of the propellant. These outcomes suggest that HIPEP based micro-thrusters works primarily due to electro-thermal energy, much like conventional PPTs.

ACQUIRED PROPERTIES

Electrically controlled Solid propellants (ESP) are potential substitutes for solid as well as liquid propellants because they combine features of both solid and liquid propellants, such as longer shelf life, higher energy density, and excellent burn rate/throttle control. ESPs can only ignited by electric current and burning is unsustainable in the absence of electric power. Wayne illustrated that the mass of ECESP combusted and burn rate are directly proportional to the input electrical power. Moreover, these propellants are unaffected by constant high temperatures as well as low energy flaming, yet they run into smouldering over continued exposure to higher temperature[11]. Initially ECESPs were intended to use in automobile air bags, as gas generators because ECESPs generate approximately 1 gas L of per gram of propellant burnt[2]. AS well ECESPs are least hazardous low toxic propellant as upon combustion they do not produce harmful compounds like oxide of chlorine.

Primary of all the characteristics acquired by ESPs is electrical conductivity. ESP should be able to conduct electric current to get ignited. Requirement for electrical conductivity depends on the application in specific area. For example, high electrical conductivity is not desirable for the bigger rocket motors. Though high conductivity is perfect for micro or pico-thrusters.

FORMULATION OF HIPEPs

HAN based Propellant

DSSP has innovated a new set of High Performance Electric Propellants generally known as HIPEP for micro to macro scale application for in-space spacecraft & satellites[3]. The most basic of all is HAN (Hydroxyl Ammonium Nitrate) based solution of solid propellant synthesized with eco-friendly chemical compounds through processing in typical chemistry equipment and cured at room temperature. As well this propellant is classified as 1.4S explosive under DOT regulation. In here, HAN functions as an oxidizer. Whilst PVA (polyvinyl alcohol) is used as fuel binder. DSSP utilized 75% of HAN and 20% of PVA for experimental works. Remaining 5% was Ammonium Nitrate (AN) used as fuel. Experimental works suggests 10% increment in I_{sp} as compared to conventional composite ECESPs. This propellant is highly resistive for electricity, so AC power was utilized to ignite the propellant.

- ***Additives***
  ESPs as discussed above has major disadvantage of its own viz. under specific conditions they can melt and become pliable. This is undesirable for the multiple extinguishment/re-ignition applications since melted propellant will eventually vaporize making it unusable for further application. Katzakian & Grix invented a new HAN based ECESP that utilize a boric acid containing cross-linking binder which functions

ISSN: 2277-9655
(I2OR), Publication Impact Factor: 3.785

as cross-linking agent for the binder (PVA)[12]. This improvised the propellant's capability to resist phase modulation at higher combustion temperatures. Moreover, 5-aminotetrazole (5-ATZ), which is amphoteric by nature was used as a stability augmenting compound. This compound was found to increase the decomposition temperature of the propellant by 20°C minimum.

- ***Co-oxidizers***
  Katzakian and Grix also studied different chemical formulations using co-oxidizers - AN (Ammonium Nitrate) and HN (Hydrazine Nitrate)[12].

ECESP OPERATION ANF CONTROL SYSTEMS

The fundamental principle of electric control of solid propellant is the phenomenon of manipulation of rate of combustion by varying the electric power supply. The most basic configuration as shown in Figure 2 comprises of two co-axial electrodes, one at the central axis through the propellant grain, generally stainless steel electrode and second one is the aluminium casing around the propellant grain. In this design central electrode is enveloped with combustible insulator plastic such that area f propellant near thruster opening remains uncovered, since combustion of propellant will start from the uncovered conductive area. The insulator will gradually burn away as sufficient current is supplied to the electrodes exposing more area for conduction of electric current.

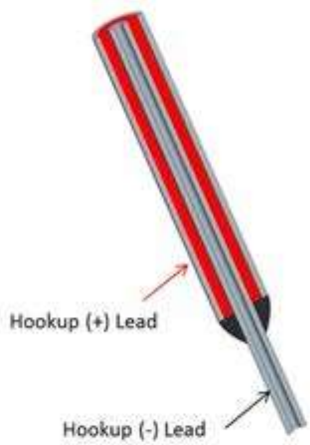

Fig 2: DSSP's First Gen Micro-thruster

The primary requirement of any ESP motor is a control system that manipulates all necessary functions for a successful flight such as throttling and burning of the propellant. In phase of present study, an electronic control system is considered which controls all functions viz. actuation of nozzle in various configuration, timing ignition/extinguishment of propellant and burn rate variation of electrically ignitable solid propellant. Moreover, electrical conductivity of the propellant varies throughout combustion process due to number of factors such as electric field, pressure, temperature, and ignition cycle. Thus a compatible power supply system should be designed which can deliver power at irregular intervals.

The central control unit of any propulsion system is known as PCM (Propulsion Control Module). It is simple PCB circuit chip that comprises of microcontrollers, logic gates, communication devices, semiconductor switches and voltage converter.

A well-known model for electrical control of solid propellants is Digital Propulsion System often abbreviated as DPS, which consist of a two-dimensional arrangement of discretely controllable micro-thrusters. Each micro-thrusters encloses a separate combustion chamber, micro-resistors and split diaphragm[13]. An ESP is discharged into the combustion chamber, where micro-resistors heat up the propellant up to critical temperature, so that it could ignite. After the ignition, combustion chamber pressure rises due to production of hot combustion gases. This pressure rise continue until the split diaphragm ruptures, causing expulsion of constituents in the form of a high-speed jet, which subsequently impart thrust to the micro-thruster.

INFLUENCE OF VARIOUS ELECTRODE CONFIGURATIONS

Performance of ECESP based thrusters is widely dependent on propellant formulation as discussed above. Yet another vital functional parameter is the electrode embodiment. Many configurations of electrode embodiment are possible viz. posts, fence, rake, ring, collar, rod, rods, combo, sandwich and side fed as discussed by Michael Dulligan et al in their patent – "Electrically controlled extinguishable solid propellant". These configurations are combination of two basic ones: *Facial-extent configuration* and *Axial-extent configuration*[14].

In the facial-extent configuration, electrodes are placed at two opposite ends of the propellant grain, leading combustion to start from end faces of the grain. Moreover, this configuration demands stability of the electrode placement at variable forces to ensure unperturbed electrical contact between propellant and electrodes. Major advantage of this type of configuration is that any kind of power supply viz. AC,

ISSN: 2277-9655
(I2OR), Publication Impact Factor: 3.785

DC or capacitive can be employed without any restrictions.

In axial-extent configuration, electrodes are placed axially through over the propellant grain. In here, electrode spacing is the most vital parameter determining the position of propellant ignition. Critically, polarity of the power supply and material of the electrode also influence the site of ignition.

APPLICATIONS

Gas Generator

The ECESPs are ideal compound for gas generation in comparison to some traditional warm & cold gas generators. ECESP unified with micro-solenoid seems to be adaptable as well as low cost warm gas generator with variable pressurization[15].

Mars Lander Retrorockets

ECESP can be employed in on-command thrust variable motors. This mars lander will comprise of cluster assembly of multiple array of valves, which further will be controlled by a feedback control system to actuate the pintle that eventually controls the nozzle-throat-area. Moreover, ESPs have had fruitful test flights as part of the OLAS (Orion Launch Abort System) and vacuum atmospheric testing in the Lunar Soft lander program[16].

SpinSat Mission

The design of SpinSat-propulsion system is centred on DSSP 1st Gen micro-thruster. For this mission, DSSP-micro thrusters were amended to the UMS (Universal Mounting System) sockets. There are total of 12 UMS, each comprises of six individually controllable micro-thrusters. Thus, there are 72 mcrothrusters over the surface of SpinSat, amongst which 8 are angled for spinning motion and 4 are straight for translational motion.

Refuellable Satellite Propellant

The ECESP are much anticipated for refuelable satellite applications since they are non-toxic and have relatively high storability. DARPA's Orbital Express Program is an illustration of SRF (satellite Refuelling) system. Additionally, use of ECESP thrusters will completely eliminate the threats of leakage of liquid propellants during docking.

CONCLUSION

ESPs have numerous gains over liquid and solid propellant thruster system. For instance, ECESP propulsion system employs very few actuating devices like mass flow control valves as compared to liquid propulsion system. Furthermore, solid rockets have relatively fewer moving parts, thus reducing complexity in building a rocket motor.

ECESPs are benign as well as compatible with customary electronic manufacturing techniques employed in making various electronic devices like batteries, capacitors, and resistors. Moreover, the ECESP electrode and grain design are well-suited to fabless manufacturing and processing, which render conventional, highly consistent solid-phase gas generators. This manufacturing coherence offers a low-cost alternative to on-earth application such as gas generators. These properties renders ECESPs as ideal propellant for in-space propulsion application.

REFERENCES

[1] Mayo, Watermeirer, Weinberg, “Electrical Control of Solid Propellant,” The Royal Society, March, 1965.
[2] Sawka, W. N., A. Katzakian and C. Grix, "Solid State Digital Cluster Thrusters for Small Satellites, Using High Performance Electrically Controlled Extinguishable Solid Propellants," Paper SSC05-XI-3, 19th Annual AIAA/USU Small Satellite Conference, 2005.
[3] Sawka, W. N. and McPherson, M., "Electrical Solid Propellants: A Safe, Micro to Macro Propulsion Technology," 49th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, San Jose, CA, July 2013.
[4] Burton, R. L., and Turchi, P. J., “Pulsed Plasma Thruster”, *Journal of Propulsion and Power*, Vol. 14, No. 5, 1998.
[5] Andrenucci, M., Lensi, R., Naso, V., and Melli, R., ‘‘Design of Solid-Propellant MPD Thrusters,’’ *Electric Propulsion and Its Application to Space Missions*, edited by R. C. Fincke, Vol. 79, Progress in Astronautics and Aeronautics, IAA, New York, 1980, pp. 586– 601.
[6] Guman, W. J., and Nathanson, D. M., ‘‘Pulsed Plasma Microthruster Propulsion System for Synchronous Orbit Satellite,’’ *Journal of Spacecraft and Rockets*, Vol. 7, No. 4, 1970, pp. 409– 415.
[7] Akimov, V., Nagel, I., Ogloblina, I., Antropov, N., Pokryshkin, A., Popov, G., and Rudikov, A., ‘‘Analysis of PPT Potentialities in Solving the Satellite Orbit Control Tasks,’’ 25th International Electric Propulsion Conf., Paper 97-146, Aug. 1997.
[8] Meckel, N. J., Cassady, R. J., Osborne, R. D., Hoskins, W. A., and Myers, R. M., ‘‘Investigation of Pulsed Plasma Thrusters for Spacecraft Attitude Control,’’ 25th

 ISSN: 2277-9655
(I2OR), Publication Impact Factor: 3.785

International Electric Propulsion Conf., Paper 97-128, Aug. 1997.

[9] Cassady, R. J., Meckel, N. J., Hoskins, W. A., Myers, R. M., Oleson, S. R., and McGuire, M., ‘‘Pulsed Plasma Thruster Systems for Spacecraft Attitude Control,’’ 10th AIAA/Utah State University Conference on Small Satellites, Sept. 1996

[10] Glascock et al,”Pulsed Plasma Characterisation of Electric Solid Propellant Pulsed Microthrusters,” 51st AIAA/SAE/ASEE Joint Propulsion Conference, July 27-29, 2015, Orlando, FL

[11] Wayne,” Solid-State, On-demand Gas Generators as *Pneumatic Batteries* for Micro-Electronic Actuators and Fluid Delivery,” Digital Solid State Propulsion LLC, Reno, NV 89509.

[12] Katzakian, Grix,” Method for controlling a high performance electrically controlled solution solid propellant,”US patent, US 20130327455 A1.

[13] Lewis et al,“Digital Micro Propulsion”, Sensors and Actuators A, Physical, 2000, 80(2) pp 143-154.

[14] Dullingan et al,” Electrically controlled extinguishable solid propellant motors **,“**USPTO, US7788900 B2.

[15] Lewis, D.H., W.J. Siegfried, R.B.Cohen E.K.Antonsson,”Digital MicroPropulsion”,12th IEEE International, Micro Electro Mechanical Systems Conference (MEMS ’99) Jan,1999.

[16] McCauley, R. J., Fischbach, S. R., “Controllable Solid Propulsion Combustion and Acoustic Knowledge Base Improvements,” Joint Army, Navy, NASA, Air Force Paper 2012-2457, May 1, 2012