Peculiar Burning Characteristics of Electrically Controlled Solid Propellants

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1 Introduction

Electrically controlled solid propellants is a type of propellant that ignites only when an external electrical power source is applied. It is used in space applications for its ability to control combustion rate and provide stable, controllable and versatile propulsion. ECSPs have many advantages over conventional solid and liquid propellants. They are highly stable and can be stored safely for long periods of time, they can be ignited with precise control over timing and magnitude, they can be turned off and on as needed, and they have the ability to produce exhaust plumes with high specific impulse values. In addition, ECSPs are non-toxic and environmentally friendly. These benefits make ECSPs attractive for use in a variety of space applications, including satellite propulsion and attitude control, as well as for use in high-performance rocket motors. Additionally, ECSPs are also preferred over traditional solid propellants due to their safer handling and storage. They have a lower ignition energy requirement, reducing the risk of accidental ignition during handling or transportation. ECSPs are also highly customizable and can be tailored to meet specific requirements for different applications, such as specific impulse, burn rate, and combustion characteristics. Furthermore, ECSPs have the potential for high performance, as the electrical energy input can be used to optimize the combustion process. This results in a more efficient combustion process, leading to higher specific impulse, improved performance and reduced residue production. Overall, the electrically controlled nature of ECSPs provides numerous advantages over traditional solid propellants, making them an attractive option for use in future rocket motor design and space applications. Additionally, ECSPs have advantages over traditional solid propellants as they can be easily shut off and restarted, allowing for precise control over the combustion process. This feature enables greater safety in handling and transportation, as well as improved performance in certain applications. ECSPs also have low ignition energy requirements, making them suitable for use in low-power systems. The combination of these properties make ECSPs a promising technology for the future of aerospace propulsion. The paper qualitatively focuses on exploring the effect of adding metal additives (Al, Mg, Ti) to a baseline ECSP (Lithium perchlorate and polyvinyl alcohol) on its burning behavior. It aims to understand the physio-chemical mechanism of ECSP combustion.

Sawka et al. [1] synthesized hydroxyl ammonium nitrate (HAN) based ECSP and showed its potential for use in micro to macro propulsion technology by conducting experiments up to 6.8 MPa in a closed bomb setup. They found that after 1.36 MPa, the ECSP combustion was self-sustaining, which is a drawback. The drawback of the self-sustaining combustion at high pressure needs to be addressed in future research. The burning rate can be adjusted by changing the electrical power input. Bao et al. [2] investigated the impact of graphite as an additive in HAN-based ECSP and found that the addition of carbon increases the thermal conductivity of the propellant, but reduces the adiabatic flame

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temperature. In the study by Gnanaprakash et al. [3], a similar baseline composition to He et al. [4] was used with tungsten as the metal additive. The addition of tungsten decreased the decomposition temperature by 60℃, but also reduced the thermal stability of the ECSP. Meanwhile, in the study by He et al. [4], experiments were conducted on the lithium perchlorate (LP) and polyvinyl alcohol (PVA) based ECSP with aluminum as the metal additive. The experiments were done in a pressure range of 0.1-5 MPa with aluminum powder below 20% in the composition. The LP based ECSP showed higher thermal stability and better electrical control compared to HAN based composition. The LiClO4/PVA/H2O had a weight ratio of 1/0.43/0.36, 1.0/0.67/0.42 and 1.0/1.0/0.5, with aluminum powder less than 20% in the composition. Glascock et al. [5, 6] developed HAN and PVA based ECSP and studied the ablation caused by arc discharge. They found that these ECSPs had a higher specific ablation per pulse. They also noted that since HAN is hygroscopic, the surface layer in the hygroscopic ECSP rapidly ablates, reducing the average specific impulse.

2 Experimental Setup

2.1 Propellant preparation

The main components of the ECSP samples in the study are Lithium perchlorate (oxidizer, 99% purity from Alfa Aesar Ltd.), Polyvinyl alcohol (binder/fuel, molecular weight 146,000-186,000, degree of hydrolysis >99% from Sigma-Aldrich Ltd.), and Boric acid (cross-linking agent). The study uses Magnesium (particle size 10 μm, from US Research Nanomaterials Inc.), Titanium (particle size 800 nm, from US Research Nanomaterials Inc.), and Aluminium (particle size 10 μm, from US Research Nanomaterials) as metal fuel additives. Different ECSP compositions were synthesized to study the effect of metal additives. The weight ratio of Lithium perchlorate to water was kept at 1:1.85 (slightly higher than solubility limit). Three ECSP compositions were created with different metal additives: 1st composition with 5% Mg, 2nd with 1% Ti, and 3rd with 1% Al. The ingredients were mixed using a planetary centrifugal mixer (Thinky ARE-310, Japan) for 45 minutes to homogenize them after LP and PVA were dissolved in water. The different compositions and metal additive content are listed in Table 1 of the study and Figure 1 shows the cured baseline composition.

Table 1: ECSP composition.

Ingredients	M0 (mass in g) Baseline	M1 (aluminium based, 1%)	M1 (Titanium based, 1%)	M5 (Magnesium based, 5%)
Distilled water	5.388	5.3228	5.3228	5.063
LP	2.912	2.8772	2.8772	2.737
PVA	1.0	1.0	1.0	1.0
Metal	0.0	0.1	0.1	0.5
Glycerol	0.5	0.5	0.5	0.5
Boric acid	0.2	0.2	0.2	0.2

Figure 1: Cured ECSP sample (baseline composition).

2.2 Setup design and Flame visualization setup

Experiments were done to qualitatively understand the behaviour of the ECSP combustion with different metal additives. There are two arrangements made to conduct the experiments. One set of arrangement of the setup includes the molybdenum bottom electrode and the top electrode made of nichrome wire. In this part of the study effect of the polarization of the DC voltage was checked. This setup arrangement with nichrome wire is shown in Figure 2 and with mesh electrode arrangement is shown in Figure 3. Experiments were conducted for different voltages. The second set of arrangement aims at directing the thrust generated by the ECSP combustion using the mesh electrode. This task was accomplished by utilizing the mesh type electrode at one end and the solid electrode at the other end. These electrodes for second arrangement were made of aluminium so that the mesh design and fabrication becomes feasible.

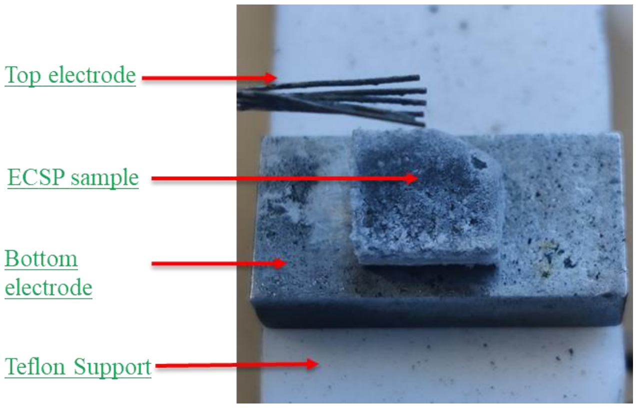

Figure 2: Setup with nichrome wire as one electrode.

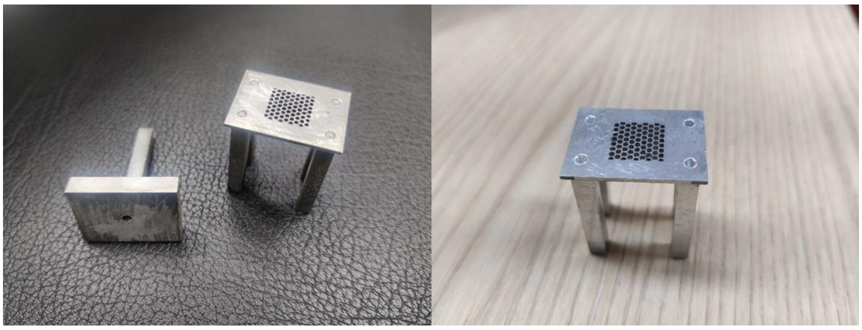

Figure 3: Mesh electrodes made of aluminium.

Experiments were conducted to visualize the flame of the tungsten based ECSP propellant under open atmospheric conditions. A nichrome wire is used as an electrode. The propellant was kept in the open atmosphere on top of the molybdenum electrode connected to the negative wire of the DC power source. The positive wire of the DC power source was connected to the nichrome wire which acted as the second electrode. A DSLR camera with 24 fps was used to capture the video of the ECSP combustion. The polarity of the nichrome wire electrode was changed from positive to negative in the subsequent experiments to check where the preferential burning occurs. Tests were conducted for the different voltage values i.e., 300 V and 200 V. It is noticed that the burning happens at the electrode where the less area is in contact with the propellant. So the flatness of the propellant surface is important. But it is seen that all the ECSP either metallized or non-metallized, they have some level of porosity and to maintain the flatness of the surface is very difficult. Mesh electrodes were fabricated to direct the thrust generated from the ECSP combustion to the desired direction. The mesh size is an important factor in this design, as it determines the size of the openings through which the product gases can escape. A smaller mesh size will restrict the gas flow due to the formation of the condensed phase layers, while a larger mesh size will allow for more uniform ejection of the product gases. This mesh design can be used to control the direction of the thrust.

3 Results and Discussion

3.1 Flame visualization with nichrome wire as one electrode

Experiments were conducted to understand the effect of polarity on the preferential burning of the ECSP at the electrodes. It was observed that the burning initiates at the electrode where the area of the electrode is less. This is because the energy power density is high at the point where the area is less. The use of negative or positive polarity would not hinder burning of the ECSP if one of the electrode area is less compare to the other electrode. This implies that the flatness of the ECSP sample surface is crucial to maintain the unidirectional combustion. Figure 4 shows the collage of images of ECSP combustion with one of the electrode as nichrome wire. Images are sequentially stacked row-wise.

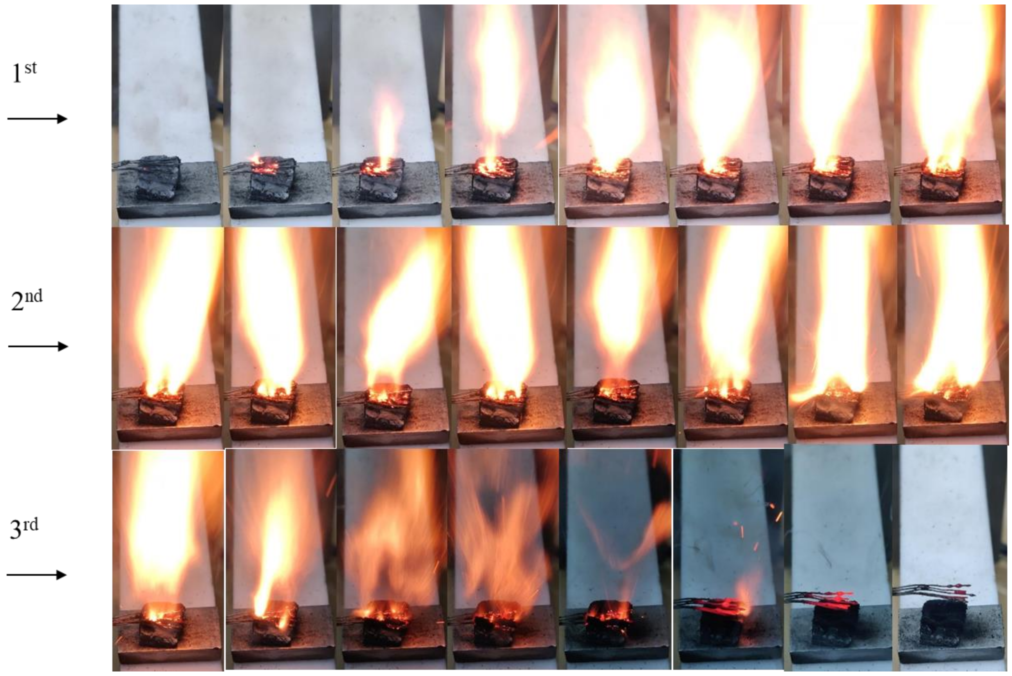

Figure 4: Collage of images row wise showing the ECSP combustion.

3.2 Flame visualization with mesh electrodes

Flame visualization experiments with mesh electrode provides insight into the usefulness of the exhasut gases during the burning. The thrust can be controlled by varying the applied voltage. To ignite the ECSP samples, mesh electrode made of aluminium have been fabricated, the voltage is supplied to the ends of the electrodes, and the combustion occurs at the electrode where the mesh is present. Sequential burning images of one of the ECSP sample are illustrated in Figure 5. The mesh size is an important factor in this design, as it determines the size of the openings through which the product gases can escape. A smaller mesh size will restrict the gas flow due to the formation of the condensed phase layers, while a larger mesh size will allow for more uniform ejection of the product gases. This mesh design can be used to control the direction of the thrust.

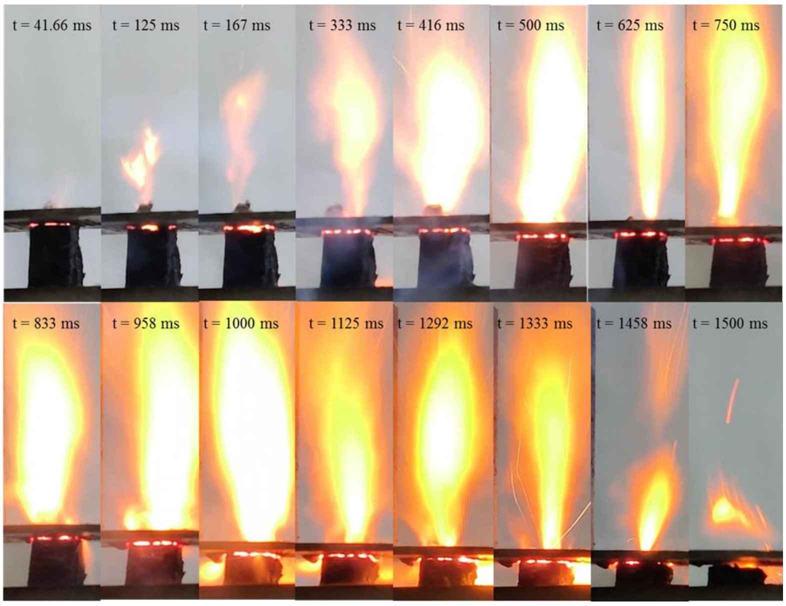

Figure 5: ECSP combustion using the mesh electrode.

3.1 Effect of magnesium in LP based composition

ECSP composition with magnesium has shown peculiar behaviour which has not been seen in any other composition so far. After the addition of the magnesium powder in the mixture of water, LP, PVA, froth formation was seen and the gases were evolving out of the mixture (probably the reaction of the magnesium with the water). After keeping the mixture with magnesium in the mixer, evaporation of the water started swift and rapid. The possible reactions occurring during the mixing of magnesium with water are as follows:

Reactions of magnesium with water: When exposed to steam, magnesium changes from magnesium to magnesium oxide and hydrogen.

$$Mg(s)+H_2O(g)\rightarrow MgO(s)+H_2(g) \quad (1)$$

When exposed to cold water, the reaction is a bit different. The reaction does not stop because the magnesium hydroxide gets insoluble in water.

$$Mg(s)+2H_2O(g)\rightarrow Mg(OH)_2(s)+H_2(g) \quad (2)$$

Reactions of magnesium with oxygen: When exposed to oxygen, magnesium turns into magnesium oxide.

$$2Mg(s)+O_2(g)\rightarrow 2MgO(s) \quad (3)$$

It was found that burning ECSP samples at different voltages resulted in the formation of a liquid layer at lower voltages, which enhanced combustion by distributing the decomposed products. This ensured adequate combustion through contact with the electrode. The liquid layer was only seen at low voltage conditions and not at high voltage conditions. It was observed that when voltage was supplied to ECSP samples, a liquid layer was formed. This behavior was not seen in ECSP samples containing magnesium, as the reaction of magnesium with water released gases that made the structure porous and reduced the electrical conductivity. With these set of experiments, it can be hypothesized that the formation for the liquid layer is an important step in the advancement of the ECSP combustion. In most of the research work, researchers have used HAN based ECSP composition. HAN is hygroscopic in nature which means that it absorbs the moisture from the surrounding which in turn when applied with the voltages increases the conductivity and thereby adequate combustion happens. Thermal analysis and chemical kinetic analysis shows that the peak of the reaction rate shifts towards higher temperature at high heating rates. Thermal analysis and chemical kinetics parameters of these samples has been evaluated and has been the part of separate paper submitted in ICDERS 2023.

4 Conclusion

The study aims to analyze the impact of adding different metal additives (Aluminum, Titanium, Tungsten, Magnesium) to an electrically controlled solid propellant (ECSP) composition on the combustion behavior. By comparing the combustion of ECSP blended with these metal additives to the baseline ECSP composition, the study aims to determine the effect of each metal additive on the combustion. It has been found that the formation of a liquid layer during combustion of ECSP samples at lower voltages enhances the combustion process by distributing the decomposed products of the lithium perchlorate and polyvinyl alcohol in the surrounding area of the ECSP where the contact of the electrode occurs, which ensures adequate combustion. However, the formation of the condensed phase liquid is only seen at low voltage conditions and not at high voltage conditions. Additionally, it has been observed that the behaviour is not seen in Mg-based ECSP samples. This is because when the Mg powder is mixed with water, it reacts with the water releasing gases, which makes the structure porous and reduces the electrical conductivity of the Mg-based ECSP sample. This unseen behaviour of Mg in ECSP samples is reported in the paper.

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