Combustion and propulsive characteristics of potential hybrid rocket propellant

Rahul Sunil₁, Aditya Virkar₁, M Vignesh Kumar₁, Iynthezhuthon Krishnamoorthy₁ and Vinayak Malhotra₁

₁Department of Aerospace Engineering, SRM Institute of Science and Technology, Kattankulathur, Chennai, Tamilnadu, India

E-mail: shadeslayerbrightscale@gmail.com

Abstract. Presently, the advancements in the field of rockets and rocket propulsion has been done to such an extent where the mission success rate is surely more than its failure. This has also led to a need for much better efficient materials (propellants) that form a major part of the rockets. The project deals with the combustion and the propulsion characteristics of the rockets. In combustion part, the experiments are conducted on normal paraffin wax candle, coated with different energetic materials in order to calculate the burn rate with the help of videography. This addition of energetic materials enhances the regression rate of candle. The propulsive characteristics, like the specific impulse and characteristic velocity, are studied through simulations carried on the NASA-CEA software in which a base composite propellant (AP/HTPB/Al) is present along with highly energetic materials. The energetic materials considered here are either fuel, binder or oxidiser which helps us to study the variance in the specific impulse and the characteristic velocity. The key parameters here are pressure, temperature, the oxidiser to fuel ratio and the composition of the material. One of the novelities of this study is to create a relation between the combustive and propulsive characteristics as there is not existing correlation between them. Other importance of this study is the concept of Hybridisation put forth to simplify the addition of material in the propellant. This concept has been studied extensively come up with a better hybrid propellant that can be used to improve the efficiency of the rocket.

1. Introduction

Improvising and bringing out the best from the limited sources that we have has been the need of the hour in the field of propulsion. Due to advancement of technologies we have been able to take the calculated risks and rise up to the task. Starting initially with just the idea of going against the gravity and eventually reaching to higher orbits in space and beyond the use of propulsion has come in handy. Learning from various failed attempts, it had been concluded that during the initial phase of rocket launch the use of solid propellant was mandatory as only then the required boost of velocity was achieved. But now, owing to the research and development in this field many different alternatives have been proposed. Even though not in use currently, due to the risk factors that are involved, these alternatives can surely come in handy in the near future with the required improvements. Till date there has been no success to chart both propulsive and combustive characteristics simultaneously. Also, the use of hybrid propellants is limited to an extent due to less productive output than required and the indulgence of high risk due to it being a potential detonator (figure 1). Because of this factor the research on hybrid composition is limited. So, there is a need to find an easier and efficient ways to carry out their propulsion.
Figure 1: Pictorial representation of high energy propellant induced rocket launch (*NASA Images).

The use of energetic candles along with the coating of various different metals closely resembles the case of the rocket engine carrying a hybrid propellant. The addition of energetic materials in the propellant makes it hybrid and also gives the boost needed to achieve the escape velocity much easily (figure 2). The earliest energetic material referred to by name is ‘Greek Fire’. It was developed by the Byzantines of Constantinopole around the 7th century (A.D.) and consisted of a petroleum distillate, thickened by dissolving resinous and other combustible materials. The development of explosives began with the formulation and use of black powder (also known as gunpowder) in about the middle of the thirteenth century. Black powder is a powdered mixture of charcoal and sulphur, which is mixed with Potassium Nitrate (KN, KNO₃) oxidizer. At the end of the 18th century and at the beginning of the 19th century the composition became more or less standardised KNO₃/C/S (75/15/10). Later in the nineteenth century, the nitration of many compounds to produce high-energy explosives were realized. Research on explosives greatly intensified during World War II. Much of the interest in the early part of the 19th century was in the effects of nitration of relatively common materials, such as silk, wool, resins, wood, cotton etc.

Figure 2. Pictorial representation and schematics of explosive materials and their applications (*www.science.com).
The basic theory of rocket propulsion is that when the fuel is burnt in the presence of oxygen, the exhaust gas released provides the thrust to propel the rocket forward. The thrust produced is equal in magnitude but moves in an opposite direction to the rocket. Due to the strong gravitational pull of the Earth, we need a really strong force to break free from the gravitational pull and exit the Earth’s atmosphere. Compared to other types of propellant, solid propellant provides an enormous amount of thrust. Hence Solid propellant is used in the stage-1 of rockets. Though the thrust cannot be controlled once the fuel is ignited, it produces massive thrust. The specific impulse of a rocket propellant is used to determine whether a propellant is ideal or not for the mission. Various missions have varying specific impulse. Specific Impulse is directly proportional to the thrust produced. This is why Specific Impulse plays a crucial role in propellant selection. The main issue with solid propellant is the low Specific Impulse generated compared to liquid propellant. Thus, the overall thrust production is reduced. To add to the disadvantages is that the reaction once initiated cannot be controlled. By adding energetic material into the base composition, we can increase the thrust and improve the overall performance of the propellant. These are materials which contain high amounts of stored chemical energy. During a chemical reaction, when bonds are broken or created energy is released, this energy can be used to propel the propellant and thus increase the thrust of the rocket.

Energetic material can be vaguely classified into three categories. That is pyrotechnic composition, explosives and propellants. In order to attain higher values of propulsive efficiency and increase the specific impulse of the rocket we use energetic material. With the use of energetic material, we can improve performance and as well as make the propellant environment friendly. Now, the addition of energetic material may increase or decrease the Isp of the propellant depending on the properties of this material. This effect of the energetic materials can come in handy when added in the different proportion at a specific period of time (figure 2). The output energy can be utilised in attaining higher ‘Isp’, thereby enhancing the efficiency of the rocket propellant. Another noteworthy aspect from the study is the behaviour of the output (the flame of the candle) which behaves differently in presence of the different materials having effect on the regression rate.

\[
I_{sp} = C_F \frac{C^*}{g} \quad (1)
\]

\[
C_F = \frac{F}{P_c A_t} \quad (2)
\]

\[
C^* = \gamma P_c A_t / \dot{m} \quad (3)
\]

The burning rate is expressed by the Saint Robert and Vielle law (Equation 4)

\[
r = a P_c^n \quad (4)
\]

Where,
- \(I_{sp}\) = Specific impulse (N-s/Kg)
- \(C^*\) = Characteristic velocity (m/s)
- \(C_F\) = Thrust coefficient
- \(F\) = Thrust (N)
- \(P_c\) = Chamber pressure (MPa)
- \(A_t\) = Area of nozzle at throat (m²)
- \(\gamma\) = Specific heat of combustion gases
- \(r\) = Burning rate
- \(a\) = Rate of burning constant
- \(n\) = Pressure exponent

From the classical work Grant and Jones [1] on low frequency diffusion flames oscillations, where different combustion parameters were experimentally explored. Appreciable work(s) on the combustion and related propulsive aspects of the propellants have been carried out. The reviews can be found in [2-10]. The development of NASA-CEA, which helps to get the propulsive characteristics of different propellants present in different composition is considered a big boon [3-4]. Recent work(s)
have focussed on the narrowing down of the base propellant further to generalize the propellant composition which has the comparatively best combustive and propulsive efficiency [9-10]. In the light of above-mentioned work(s), one aspect which has not be emphasized so far is, carrying out such hybrid propellant experiment on large scale by developing and utilizing a simpler and affordable setup. The work reinstates hybridization concept in the form of combination of two or more distinct elements (here propellants as the combination of two or more different composition). Present study is an effort to relate the propulsive and combustive characteristics which tend to be the most important factor in the space propulsion and operations. The use of different energetic materials to provide a varied range of characteristic in propulsion is accounted. The work is motivated by the elevated propulsive performance by accounting the modulation in the combustion characteristics. The specific objectives of the work are:

1) To chart both the combustion and propulsive characteristics simultaneously.
2) To check the effect of different energetic materials on the rocket propellant.
3) To propose a better and safer propellant.

2. Experimental setup/Simulation and Solution Methodology
The study was carried out in two parts viz., investigation of combustive characteristics using experiments and observations of propulsive characteristics using simulations. While studying the propulsive characteristics, the specific impulse and the characteristic velocity were kept in the main frame. The other propulsion related parameters such as the temperature, pressure, oxidizer to fuel ratio were all pre-defined and were considered to be constant throughout. To efficiently carry out the study, the simulations were carried out on the NASA-CEA Software and undermentioned inputs were considered.

1. The fuel was taken as paraffin wax and the oxidiser as Air.
2. Chamber pressure (5-25bar/5 bar increment).
3. Supersonic Nozzle area ratio (10).
4. Oxidizer/Fuel ratio (1-14.82/1 increment).
5. Addition of energetic materials in the fuel by a percent of 15%.

For the ordered hybridization, the following is the conditions applied in the simulator:

1. The base propellent taken is Al/HTPB/AP-(15/15/70).
2. Chamber pressure (5-25bar/5 bar increment).
3. Supersonic Nozzle area ratio (10).
4. Oxidizer/Fuel ratio (1-2.33/1.33)

The base propellant and its proportion selected is the one that had the best outcome from the previous study of propellant. When that propellant is further added with fuel and oxidiser in different proportion the specific impulse is altered further giving a new optimized value. The other conditions are not changed as only the effect of composition of propellant on the impulse and velocity is to be studied. These constant values are also fixed from the previous data at which the base propellant had the optimized output. For combustive characteristics, systematic experimentation was carried out (figure 3). An energized candle was used which replicates the rocket engine closely. This candle was marked at a uniform distance and with the help of videography the regression rate of the candle was observed. Further, this candle was uniformly coated with fine powdered grain of different materials and its effect was observed on the burn rate. Special care was taken that no other external factors affect the candle as all the experiments were carried out in close room. Also, the distance of camera for videography was kept constant throughout the study. The specifications of the pilot fuel (here, energized candle) are as undermentioned.

1. Height of candle: 4.5 cm.
2. Area of candle surface: 0.196 cm².
3. First marking on candle from 0.5 cm from top.
4. Next three readings on candle at 1 cm distance from each other.
5. An external light source is used to make the markings visible in the videography.

![Figure 3](image)

**Figure 3.** Experimental setup (a) marked candles as pilot fuel, (b) aluminium coated paraffin candle, (c) normal candle burning.

It is important to note that thorough environmental normalcy was maintained in experimentation and data represents repeatability of the order three.

3. Result and Discussions

Prior to the main study, the validation of the simulation predictions with the existing work on high energy materials was carried out (Table 1). Simulations were carried out by changing the base composition (Al/HTPB/AP) by adding energetic materials in the fuel, oxidiser and binder part of the propellant to understand the change in ‘Isp’ and ‘C*’ values of the propellant.

It was established that the previous simulation readings were accurate and that the software has been accurate to a very close degree.

| Propellant Composition | Experimental/ Theoretical (secs) | NASA-CEA Simulations (secs) |
|------------------------|---------------------------------|-----------------------------|
| AP (80%)/Al (20%) (by volume). K. S. Williams, PhD thesis, Texas, A&M University, 2012. | 246 | 242.59 |
| AP/HTPB/Al [70/10/20] (mass). K. S. Williams, 2012. | 258 | 247.08 |
| AP/HTPB/Al [70/15/15]. P. Kuentzmann, 2002. | 265 | 260 |
| AP/HTPB/Al [64/14/18]. Venkatachalam et. al., 2002. | 265 | 263.37 |
| AP/HTPB/Al [(50-10)/ (35-75)/15]. Nevada Aerospace science associate(nassarocketry.com). | (238-175) | (230-170) |
| AP/HTPB/Al [68/14/18] at (Pc=6.89MPa) [www.lr.tudelft.nl](http://www.lr.tudelft.nl) | 266 | 264.02 |
| AP/PBAN/Al [70/12/16] at (Pc=6.89MPa) [www.lr.tudelft.nl](http://www.lr.tudelft.nl) | 267 | 263.97 |
Table 2. Burn rate with respective Specific Impulse.

| Material used | Burn rate (m/s) | Specific impulse(secs) |
|---------------|----------------|------------------------|
| Aluminium     | 0.0119         | 210.48                 |
| Copper        | 0.0146         | 198.06                 |
| Nickel        | 0.0087         | 194.06                 |
| Iron          | 0.0122         | 198.33                 |

Figure 4. Variation of specific impulse and burning rate.

With systematic collection of data from both the experiment and respective simulation, the variation of burn rate with specific impulse was plotted (figure 4). For the results obtained, curve fitting tool was utilized and the equation of the curve was found with respect to specific impulse (equation 5).

\[ y = 0.0001916382 \times x^3 - 0.1155857\times x^2 + 23.22478\times -1554.638 \]  

(5)

where,

’y’ is burn rate and ‘x’ is specific impulse.

Next, the effectiveness of the equation was validated as the ‘Isp’ of the normal paraffin wax candle was calculated and substituted to find the burn rate (y). It was found to be 0.0082 m/s which is reasonably well match with the minor error less than 5%. Thus, the equation can be used extensively to provide good physical insight for variety of missions and operations.

3.1 Propellant composition Hybridization

The study was extended to the prediction of new hybrid propellant compositions through novel hybridization methodology presented comprising of Ordered and Distinct hybridization. The addition of energetic materials in the base propellant compositions are widely known to result in three types of effects on performance viz., increasing, decreasing and neutralizing. Thus, the energetic materials are classified as in categories of Activators, Inhibitors and Neutralisers. Activators increases the performance, Inhibitors decreases the performance and Neutralisers provide the neither increasing nor decreasing effect on performance of the propellant. It is important to note that, for different base compositions, a selected energetic material can behave in any of the above mentioned three categories.

3.1.1 Ordered Hybridization. Ordered hybridization details, the base composition is changed and the resulting optimized value composition is selected as the new base composition. The change of
composition defines the order. In ordered hybridisation, Al/HTPB/AP (15/15/70) was used as the base composition which produces a specific impulse of 262 seconds.

(b) Second Order: Taking the optimised composition viz., Ti/HTPB/AP (15/15/70) from the first order simulations, second order hybridisation was carried with addition of compounds viz., Aluminium Hydride (AlH$_3$), Aluminium Oxide (Al$_2$O$_3$), Beryllium hydride (BeH$_2$), Lithium Hydride (LiH), and Silicon carbide (SiC) were added with the fuel and varied in composition to study the effect on the performance of the hybrid propellant composition (figure 6). Looking at the plot one can note that, hydrides largely behave as activators by resulting in enhanced performance whereas the compound (Al$_2$O$_3$) behaves as an inhibitor. Qualitatively, addition of all metal hydrides follows similar increasing trend with maximum at 100% addition in the composition. It was observed that of all hydrides, Beryllium Hydride provides the maximum activator effect with 21.36% rise, followed by the Lithium Hydride with 10.38% rise and Aluminium Hydride with 4.48% rise. It is interesting to note that addition of Carbides results in gradual increase in performance (here, Silicon Carbide with maximum 4.30% rise at 100% addition). Likewise, addition of oxides here Aluminium oxide, results in significant 6.92% drop in performance with 100% addition. However, in case of Aluminium Oxide, the maximum inhibitor effect was noted with at 11% concentration, resulting in 10.83% drop and matching up with the normal pattern with further rise in % concentration. The variation in
performance with specific impulse change was validated with the variation of Characteristic velocity (C*) with variation in composition (figure 6(b)) and which corroborates the effect. From the second order hybridisation, BeH$_2$/HTPB/AP (15/15/70) was selected as the base composition for the third order hybridisation.

(c) Third Order: Taking the optimised case BeH$_2$/HTPB/AP (15/15/70) from the second order hybridisation as the base case with a specific impulse of 326 seconds. Next, the liquid additives viz., Chlorine trifluoride (ClF$_3$), Diborane (B$_2$H$_6$), Hydrogen Peroxide (H$_2$O$_2$), Hydrogen (LH$_2$) and Nitrogen Tetra oxide (N$_2$O$_4$) were tested with the fuel into the base case for different variation and studied (figure 7). Looking at the plot once can note that, except Liquid Hydrogen all remaining selected liquid additives behaves as an inhibitor with steady reduction in performance with 100% addition. However, liquid hydrogen provided improved propulsive characteristic up till a certain concentration addition in the propellant composition. As potential inhibitors, liquid Chlorine trifluoride resulted in maximum drop of 22.21%, followed by Liquid Hydrogen Peroxide (22.15%), liquid Nitrogen Tetra oxide (21.23%) and liquid Diborane (17.20%). Interestingly, addition of liquid Hydrogen till 6% concentration results in activator effect with maximum of 2.66% at 3% liquid hydrogen concentration in the propellant composition. However, with further increase in liquid hydrogen concentration, similar reducing pattern was observed with maximum 19.47% drop. The variation in performance with specific impulse change was validated with the variation of Characteristic velocity (C*) with variation in composition (figure 7(b)) and which corroborates the effect. From the third order hybridisation, H$_2$/BeH$_2$/HTPB/AP (3/15/15/70) was selected as the base composition for the fourth order hybridisation.

(d) Fourth Order: From the third order hybridisation, H$_2$/BeH$_2$/HTPB/AP (3/12/15/70) with a specific impulse 334.4 seconds, was taken as the base composition for fourth order hybridization. For the fourth order hybridisation, the oxidiser was altered by adding liquid oxidiser viz., Ammonium nitrate (NH$_4$NO$_3$), Perchloryl fluoride (ClO$_2$F), Liquid Oxygen (LO$_2$), Liquid Ozone (LO$_3$), and Unsymmetrical dimethylhydrazine (UDMH) into the composition (figure 8). Looking at the plot one can note that, of all the liquid additives selected to be amalgamated with the oxidizer in the composition, Perchloryl fluoride (ClO$_2$F), Liquid Oxygen (LO$_2$), Liquid Ozone (LO$_3$), act as energetic activators whereas, Ammonium nitrate (NH$_4$NO$_3$), and Unsymmetrical dimethylhydrazine (UDMH) behaves as energetic inhibitors. It is interesting to note that addition of all external materials results in
similar monotonous increasing or decreasing trend with maximum effect at 100%. The Activator effect was maximum noted in Liquid Ozone (8.27%) followed by Liquid Oxygen (3.32%) and Perchloryl fluoride (2.45%). Whereas, for inhibitor effect, the maximum was noted with Unsymmetrical dimethylhydrazine with 21.03% drop, followed by Ammonium nitrate (3.87% drop). The variation in performance with specific impulse change was validated with the variation of Characteristic velocity ($C^*$) with variation in composition (figure 8(b)) and which corroborates the effect.

![Figure 7](image1.png)

**Figure 7.** Variation of (a) $I_{sp}$ vs concentration of material (Liquid additives), (b) $C^*$ vs concentration of material (Liquid additives).

![Figure 8](image2.png)

**Figure 8.** Variation of (a) $I_{sp}$ vs concentration of material (Liquid Oxidizer), (b) $C^*$ vs concentration of material (Liquid Oxidizer).

### 3.1.2 Distinctive Hybridization

In distinctive hybridisation, the addition of component is specifically chosen, in order to improve the pre-existing propellant composition. In this the material property plays an important role in selecting the component.

*(a) Role of activators in fuel composition: Al/HTPB/AP (15/15/70) was used as the base composition and selected materials viz., Carbon (C), Iron (Fe), Boron (B), and Lithium (Li) were used as energetic...*
materials and amalgamated with fuel concentration in the propellant composition (figure 9). Looking at the plot, one can note that, addition of activators results in monotonous increase in the propellant performance. The rate of increase varied with different materials. The maximum performance for all cases was noted with 100% addition in the fuel section. Quantitatively, the maximum activator effect by an external catalyst was noted with addition of Carbon (38.91% rise), followed by Boron (30.46%), Lithium (24.91%) and Iron (2.92% and 4.67% with 11% concentration addition). The variation in specific impulse with addition of energetic catalyst was verified with the Characteristic velocity(C*) variation (figure 9(b)) which matches well.

(b)Role of inhibitors in fuel composition: The role of external catalysts as Inhibitors was also tested for Al/HTPB/AP (15/15/70) was used as the base composition with selected materials viz., Magnesium (Mg), Gallium (Ga), Sulphur (S), and Potassium (K) were used as catalyst and amalgamated with fuel concentration in the propellant composition (figure 10). It was observed that the addition of inhibitors results in monotonous reduction in the propellant performance. The rate of drop varied with different materials. The maximum performance drop for all cases was noted with 100% addition in the fuel section. Quantitatively, the maximum inhibitor effect by an external catalyst was noted with addition of Gallium (16.12% drop), followed by Potassium (8.35%), Sulphur (5.93%) and Magnesium (2% drop). The variation in specific impulse with addition of energetic catalyst was verified with the Characteristic velocity(C*) variation (figure 10(b)) which matches well. The study was extended further to the investigation of Gaseous catalysts when amalgamated with the fuel and oxidizer in the base composition. The base composition was kept same as Al/HTPB/AP (15/15/70). The role of gaseous material catalysts was probed. Figure (11 & 12) highlights the variation of specific impulse and Characteristic velocity with variation in catalyst concentration.

(c)Role of gaseous materials in fuel composition: Chlorine and Hydrogen were used and added in the fuel section of the propellant composition. Figure 11 shows the effect with Chlorine resulting in monotonous drop with maximum of 5.95% drop at 100% addition in fuel section. However, the addition of gaseous Hydrogen exhibits the activator effect with only higher than base composition performance values at different concentrations. The maximum was observed at 4% fuel concentration of 5.15% rise while. 100% addition in fuel section results 4.22% rise.

(d)Role of gaseous materials in oxidiser composition: Chlorine (Cl₂), Fluorine (F₂), Hydrogen Peroxide (H₂O₂), and Carbon Dioxide (CO₂) gases were used as catalysts and added in the oxidizer.
section of the propellant composition. Figure 12 shows the effect with Gaseous Chlorine and Carbon Dioxide, behaving as retardants/inhibitors when amalgamated with propellant oxidizer. Whereas, the addition of gaseous Fluorine and Hydrogen Per-oxide results in rise in performance. Maximum inhibitor effect was noted with addition of Carbon Dioxide (43.54% drop) followed by Chlorine (40.12% drop), with 100% addition in oxidizer section of the composition. For activator effect, gaseous Fluorine yields (16.16% rise) followed by Hydrogen Per-oxide (6.86% rise). It is important to note that the activator effect noted is steady with fixed change of rate of change.

The catalyst effect on the propulsive performance can be attributed to the relative combustive changes through modulations in the reaction mechanism. The behaviour of a particular high energy material as an activator, inhibitor and neutralizer largely depends upon the combustion chemistry of the base compositions with energy transition and interactions involved.

Figure 10: Variation of (a) Isp vs concentration of concentration of material (Inhibitors), (b) C* vs concentration of concentration of material (Inhibitors).

Figure 11. Variation of (a) Isp vs concentration of concentration of material (gaseous fuel), (b) C* vs concentration of concentration of material (gaseous fuel)
4. Conclusions
Thorough experiments were carried out and were validated with the help of simulation software NASA CEA. The consequence of the addition of energized matter to the subject candle was studied and based on that the best composition for the rocket engine was proposed having much better output than the homogeneous component. The study has helped us study the effect of energetic materials in propellants and that they can be used to increase the efficiency and performance of present rocket propellants. The relation proposed between the propulsive and combustion characteristics created, even if it cannot be used extensively, can be used as a conditional equation and with more improvements, the error margin can be reduced further from 5%. The new concepts of ordered and distinct hybridization can be used to study the addition to the base propellant in more systematic and simplified manner. The distinct hybridization can be used to understand the effect of activators, inhibitors and neutralizer quite extensively. Further, up until now the base propellant Al/HTPB/AP was considered the most efficient propellant (262 seconds), but by using energetic materials in the appropriate composition can increase the performance to almost 363 seconds, rise of almost 38%. For better space exploration, addition of energetic materials is the need of the hour. The inefficiency of hybrid rocket propellant due to low regression rates can be tackled by the addition of energetic materials. The study helps in the possibility of improving performance and efficiency in the field of rockets, low earth satellites, research programs and fire safety among other applications.

5. References
[1] Grant A and Jones J 1975 Low-frequency diffusion flame oscillations *Combust Flame* 25 153–160.
[2] Omata S 1988 Entrainment among coupled limit cycle oscillators with frustration *Physica D*, 31 397–409.
[3] Gordon S and Bonnie J M 1994 Computer Program for Calculation of Complex Chemical Equilibrium Compositions and Applications NASA RP-1311.
[4] Bonnie J M and Gordon S 1996 Computer Program for Calculation of Complex Chemical Equilibrium Compositions and Applications II *User's Manual and Program Description* NASA RP-1311-P2.
[5] Braithwaite P C Hatch R L Lee K and Wardle R B 1998 Development of High-Performance CL-20 Explosive Formulations 29th *Int. Annual Conf. ICT, Karlsruhe, Germany.*
[6] Maxworthy T 1999 The flickering candle: transition to a global oscillation in a thermal plume J. Fluid Mech. 390 297–323.

[7] Kitahata H, Taguchi J, Nagayama M, Sakurai T, Ikura Y, Osa A, Sumino Y, Tanaka M, Yokoyama E, and Miike H 2009 Oscillation and synchronization in the combustion of candles J. Phys. Chem. A 113 8164–8168.

[8] Ghosh S, Mondal S, Mondal T, Mukhopadhyay A and Sen S 2010 Dynamic characterization of candle flame Int. J. Spray Combust. Dyn. 2 267–284.

[9] Banerjee S, Ramanan V and Malhotra V 2017 Energetic Composite Solid Propellant International Journal of Aerospace and Mechanical Engineering 4.

[10] Gajjar P and Malhotra V 2018 Advanced upper stage energetic propellants IEEE Aerospace Conference.