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Design and Performance Analysis of Aluminized Sugar Aided Rocket Propulsion Using MATLAB

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Abstract: ***The field of rocketry is one of the booming and challenging industry today. The developments in rocket propulsion is finding an enormous development in the present scenario for its full application. The design of a solid rocket motor involves a plenty of equations, which makes it a complex phenomenon. This work uses MATLAB to stimulate the ideal equations which governs the performance of the solid rocket motor and help improving the same performance before it is been considered for production. This helps in understanding the working of of the rocket along with the reduced cost and operating damages/explosion. This work deals with the study of propellant with inclusion of aluminium which acts as a metal fuel along with the basic potassium nitrate and sucrose which is used as basic propellant in several rocketry experiments. The inclusion of aluminium shows a agreeable increase in specific impulse and thrust co-efficient. The specific impulse is found to be 184.9 Sec with the thrust co-efficient of 2.1.***

Keywords: Aluminium, MATLAB, Solid Propellant, Specific Impulse, Thrust Co-efficient

1. Introduction

Solid propellants rocket motor is a better way for obtaining high thrusts for a short period of time. They are the reaction engines which obtain thrust based on Newton's 3rd law. It is a type of aircraft that ejects high velocity matter to develop the required thrust. The ejected matter is nearly a gas mixture produced during the combustion of propellants in the combustion chamber. The propellant is usually a mixture of fuel and oxidizer which is used to convert the fuel into useful thermal energy and gaseous by-products. These gases which are developed under high pressure and low velocity in the combustion chamber are expanded in the nozzle area where it is converted to low pressure high velocity gases.

Sucrose and Potassium Nitrate is used as basic propellant in the field of experimental rocketry where sucrose is a fuel and potassium nitrate acts as oxidizer. Various experiments are conducted using this basic propellant and the results provide a desirable result of specific impulse. There is a need for a composite propellant which provides increased specific impulse for the basic propellant mentioned above by including certain additives which increases the overall rocket performance characters. The objective is to predict the performance characteristics of this solid rocket motor with aluminized propellant.

Depending on the particular propellant, adding small particles of metal like aluminium, theoretically the specific impulse can be increased by 9%-18%. Aluminium is added to the propellant to increase the energy source of the propellant. The gaseous combustion products of aluminium condenses to liquid form and adds considerable amount of heat liberated during the combustion of propellant in the combustion chamber. Also the condensed products of aluminium provides for a stable flame temperature. The basic ratio of fuel and oxidizer propellant mixture is 65/35. In this case aluminium is added to the main fuel (sucrose) to about 15% of the overall propellant mass. The addition of aluminium also increases the density of the propellant and their-by increases the combustion properties.

2. Literature Survey

The operation of sugar propellant is similar to the convectional propellants used in large scale. However, due to the application of sugar propellants possess few problems. One of the major issue is the production and storage of solid propellants.The innovator's education and skills led to the discovery of important evolution of sugar propellants and exposure to their contemporary problems.

J.D.Hurley, as stated in The History of Solid rocket propellant rocketry, the evolution of solid propellant rocketry took place during the World War II, the research on large solid rockets capitalized on castable double base propellants. The discovery that adding large amount of aluminium significantly increased the specific impulse of a castable composite propellant which would further aid in larger missile technologies. His study shows that most of the people in rocketry with a technical expertise know only a part of history of the subject.

According to his study, the work on tactical missiles in the area of castable double propellants which occurred at Naval Proving Ground in Caltech during the World War II has been very beneficiary. Further, Keith Rumbel and Charles Henderson, the two engineers in Atlantic Research Corporation working in contract with US navy found that addition of Aluminium significantly increased the specific impulse of a castable composite propellant using Aluminium, Ammonium Perchlorate and Polyvinyl chloride.The solid fuels are the safest reliable and cheapest way to explain system of propulsion. Mixture of Potassium Nitrate and Sugar is one of the efficient propellant.

According to **TamirHussain and Jay Philips,** who were working on the experimentation of potassium based rocket propulsion, the change in stoichiometric ratios of the propellant and oxidizers will affect the thrust casing temperature and stress along with combustion chamber pressure.

The imbalance in the ratio of the propellant components reduced the burning rate of the propellant as the chemical reactions between the propellant component changes. Potassium nitrate is not flammable and has low health rating. It has the instability rating of 3 and will be contained in small quantities to reduce effects of explosion. Potassium carbonate released during the combustion is also not flammable, but since it absorbs water vapor from the combustion gases it gets diluted.

The characteristics of aluminium combustion studied by **M.W. Beckstead** of Brigham Young University, USA, the fundamental concepts that control the aluminium combustion were discussed. The two major phenomenons observed during the combustion of aluminium were the condensation and deposition of aluminium oxide and due to this deposition, the velocity of the particles oscillate. The ignition and combustion depends on the melting point of the metal fuel.

The following things were observed in their studies,

1) Aluminium combustion products condense to liquid aluminium oxide and this condensate contributes to the increased amount of heat released during the combustion.
2) The condensate products can deposit particle surface to form an oxide cap which distort the gas velocity.
3) The dissociation of condensed products maintain constant flame temperature for the given gas temperature.

Hence, analyzing the above points, the combustion model cannot be compared with simple hydrocarbon droplet model. The study conducted by **Ermakov.et.al** shows that the ignition temperature varies nearly around 2000K.

In 2002, **Stuart Leslie** and **James Yaron** submitted a proposal to the TRA Board of Directors for the inclusion of potassium nitrate sugar propellant. They had explained about the methods of preparation of sugar propellants. Their study showed that the sugar propellant characters matched the theoretical design and that effective motor can be developed with minimum error. They conducted several static tests and the thrust curves closely relate to the predicted curve.

They obtained an experimental result of 164sec of specific impulse for 65% of potassium nitrate with 35% of sorbitol, which shows that it is possible to improve specific impulse with the variation in the ingredients.

3. Structural requirement and Assumption

3.1 Structural Requirement

It is necessary to design the rocket motor in such a way that it must be able to withstand the internal loads and thermal stresses applied on the internal wall of the motor. In some locations the casing must be able to withstand the high pressure created as a result of combustion.

In this case, the casing design is determined based on the MATLAB analysis made utilizing the mechanical properties of the casing material used and the geometrical parameters and equating them in the closed form of equations.

The casing is sized using stainless steel. The design of component is based on the maximum thrust and pressure to which the rocket motor is subjected during the combustion.

3.2 Ideal rocket unit assumption

1) The products of combustion are homogenous.
2) The combustion gases obeys the perfect gas law.
3) The specific heat ratio of the combustion gas is constant throughout the motor.
4) No heat is lost through the wall, and hence the flow is adiabatic.
5) The change in temperature and pressure is directed axially, and hence theflow through nozzle is one dimensional.
6) There is no friction between exhaust gases and the rocket motor wall, and all the effects of boundary layers are neglected.
7) The drag co-efficient is assumed to be 0.4, whereas the actual drag co-efficient is based on tests.
8) Thrust produced is constant throughout the combustion.

4. Propellant Selection

Propellants are selected and often tailored to specific applications. The change in chemical ingredients changes their physical properties and there by directly altering the burning rates and performance.

The chosen propellant for the calculation here is a convectional type composite propellant which contains 15%-20% sucrose, 60%-70% potassium nitrate and 5%-10% of aluminium.

Several experiments have been conducted using sucrose and potassium nitrate as propellants. But slight change in the stoichiometric ratio along with the inclusion of metal fuel, increases the overall specific impulse of the rocket for the same mass of the latter propellant. The changes in the stoichiometric ratio results in higher density and specific impulse along with the wider burning rates even though they are smoky.

4.1 Chemical reaction

The combustion reaction equation for KNO_3, $C_{12}H_{22}O_{11}$ and Al is given below

4.2 Molecular Weight

The molecular weight of reaction products are given in Table1.

Table 1: Molecular mass of reactant products.

Reaction products	*Molecular mass (g/mol)*
H_2O	18.015
CO_2	44.01
N_2	28.013
AlO_2	58.98034
K_2CO_3	138.205

The molecular weight and temperature of the gases determine the exhaust velocity. Higher the molecular weight, higher will be the exhaust velocity. It can be noted that the addition of aluminium, the overall temperature of the combustion reaction increases which increase the velocity of gases.

5. Motor Casing Material

The motor casing material and sizing is dependent on the thrust load and chamber pressure/temperature. The stresses developed should be well within the yield strength and ultimate strength of the material chosen for casing.The current rocket motor is a small scale rocket design based on the experimental results for Sucrose and Potassium nitrate as propellants.

A small scale of 40mm outside diameter, wall thickness of 5mm and the combustion chamber length is 150mm. Based on the results given by SRM software, stainless steel is chosen as casing material.

Table 2: Properties of stainless steel

Properties	*Values*
Yield Strength (MPa)	517
Ultimate Strength (MPa)	862
Modulus of Elasticity (MPa)	186.3
Poisson ratio	0.27

The propellant parameters entered in MATLAB are given in Table 3 below.

Table3: MATLAB parameters

Parameter	*Value*
Burn rate pressure exponent	0.4
Weight of propellant (kg)	0.158
g_o (m/s^2)	9.8066

6. Results and Discussion

After executing the code successfully in MATLAB, the code is solved to obtain the unknown parameters. The engine parameters calculated using MATLAB is shown in the Table 4.

Table 4: Parameters obtained from MATLAB

Parameter	*Value*	*Unit*
Total impulse	29226.069	N-sec
Specific impulse	184.97	sec
Density	2.04	g/m^3
Exhaust velocity	1372.9	m/sec
Specific heat ratio	1.21	
Burn time	13.48	sec

These rocket parameter such as altitude, chamber pressure, thrust coefficient and exhaust velocity are plotted against the burning time to study their characteristic behavior over the combustion period. The designing of the rocket motor becomes easier by choosing the suitable values from the plotted graph.

For a solid ground launched rocket, it can be seen that rocket starts to gain altitude gradually with respect to time. It remains linear for a while and keeps ascending further. The change in transition can be noticed during the flight period.

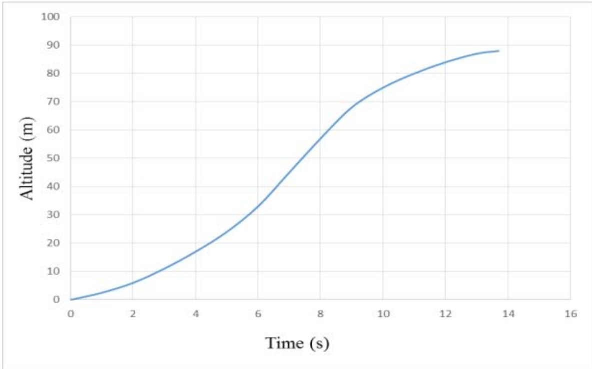

Figure 1: Altitude vs. Burning time

This transition is because the propellant is considered as two segments and with the end of combustion of first segment, there is a transition from first segment to second segment and hence further increase in altitude can be observed. The flight of the rocket ends at the propellant burnout.

The change in chamber pressure of the rocket is shown in the Figure 2. It can be seen that the chamber pressure reaches about 19 MPa. The chamber pressure remains constant with respect to burning time and the exhaust velocity. The graph helps in finding the motor casing design parameters. At the end of the burning with the total consumption of propellant the pressure starts to decrease which can be noticed with the declining trend in the graph at the burnout time.

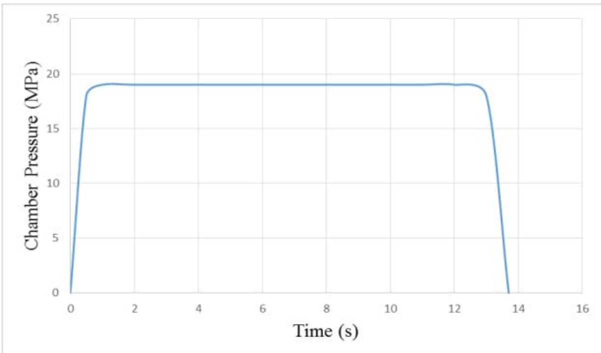

Figure 2: Chamber pressure vs. Burning time

Thrust co efficient is a dimensionless factor which represents the efficiency of the nozzle. It is the thrust produced per unit of chamber pressure and throat area. Due to the constant burn rate, the chamber pressure and thrust produced remains constant throughout the combustion time and hence it can be seen in the Figure 3 that the thrust co efficient remains constant throughout the burn time.

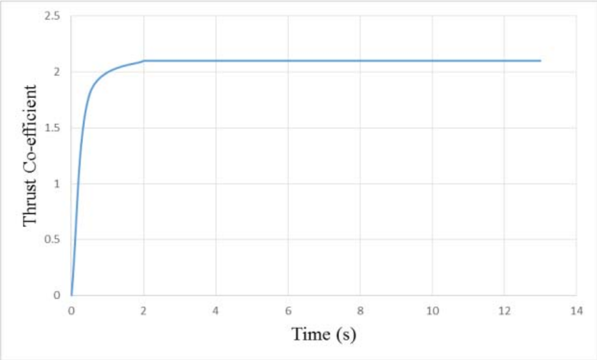

Figure 3: Thrust coefficient vs. Burning time

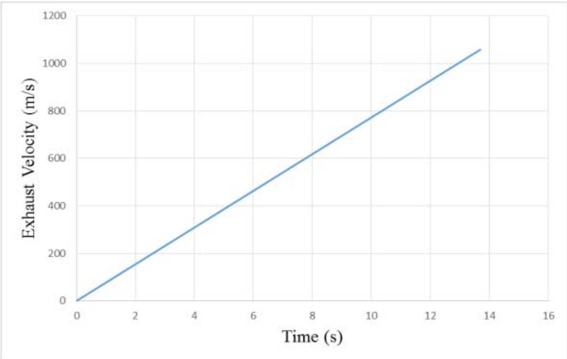

Figure 4: Exhaust velocity vs. Burning time

The factor which decides the efficiency of the rocket motor is exhaust velocity. Exhaust velocity is the velocity of exhaust gases produced which is ejected out of nozzle per unit consumption of propellant. The variation of exhaust velocity against burning time is shown in Figure 4.

As the velocity always remains linear with respect to time, it can be noted from the figure that there is a linear increasing trend in the velocity till the burn out. This is because; as the propellant is consumed during the combustion the gases produced is ejected out through nozzle. Hence there exists equilibrium between chamber pressure and the exhaust gases.

7. Conclusion and Future Work

7.1Conclusion

1) The important parameters like density, specific impulse, exhaust velocity and thrust of the rocket is found to be increased with the inclusion of aluminium.
2) The obtained values are quite higher than the results obtained for the analysis of basic KNO_3 and Sugar propellant.
3) Considering the acceptable limits, the specific impulse is 184.9 sec.
4) The combustion temperature is found to be increased by 200 ºC with inclusion of aluminium. This increase in temperature is responsible for the high temperature of exhaust gases which increases the thrust produced.

7.2 Future Work

1) Experimentation can be conducted to validate the same paper.
2) Further studies on erosion burning and burning rate can be carried on.
3) For increased scale of rocket design, the rocket can be improvised for futuristic rocket propulsion and bio rocketry by replacing KNO_3 by another bio degradable element.

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