Experimentation of a Large Lab-Scale Hybrid Rocket Engine Utilizing Paraffin-Based Fuels Containing High-Energy Material

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Abstract

The focus of this research work was to evaluate paraffin-based fuel with additives and their overall performance with gaseous oxygen in a hybrid rocket. Parameters such as specific impulse and combustion efficiency were determined for each test for sodium amide and potassium borohydride additives. For performance over various oxidizer-to-fuel ratios and initial flux conditions, a weight percent of 20% was chosen. For sodium amide, weight percent of 20%, 30%, and 40% were tested to evaluate how regression rate changed weight total additive weight percent. It was concluded that increased addition of sodium amide and potassium borohydride led to an increase in chamber pressure which is a result the higher increase in flame temperature with weight percent compared to the molecular weight of the products

Introduction

Motivations for Studying

- ***Fuel regression*** is a heavily studied topic in the hybrid propulsion field. Regression rates of various fuels vary with ***fuel, additives***, and ***oxidizer composition***.
- There is a need to increase the regression rate and mass burning fractions of solid fuels in hybrid systems

Project Objectives

- Ascertain performance data, including fuel regression rate, specific impulse (Isp), characteristic velocity (C*), thrust, chamber pressure, and efficiencies of sodium amide and potassium borohydride additives at different weight percent in paraffin-based fuel.

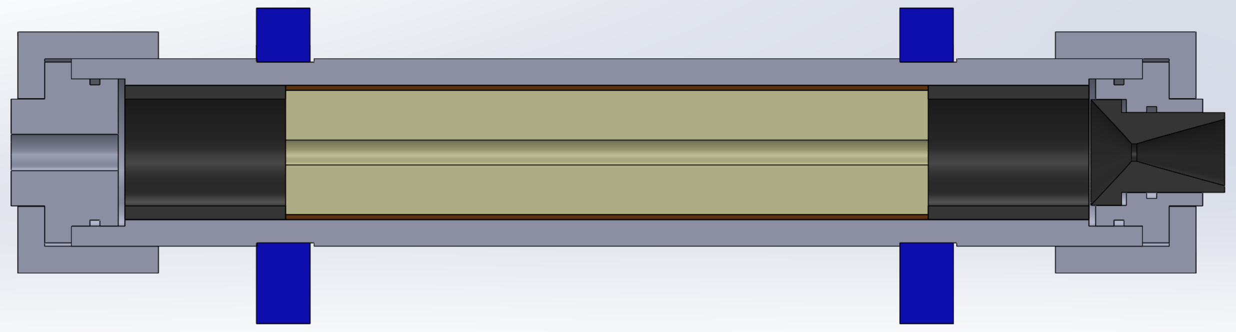
Background:

- With traditional solid rocket propulsion, the fuel and oxidizer are mixed and in contact with each other. Solid rockets are unable to be shut down once ignition occurs due to this.
- In a hybrid rocket engine, fuel and oxidizers are ***stored separately*** in two different phases. This allows the engine's ***thrust and fuel burning rate to be throttled*** to maximize vehicle performance. More importantly, hybrid engines can be ***shutdown during an emergency***.

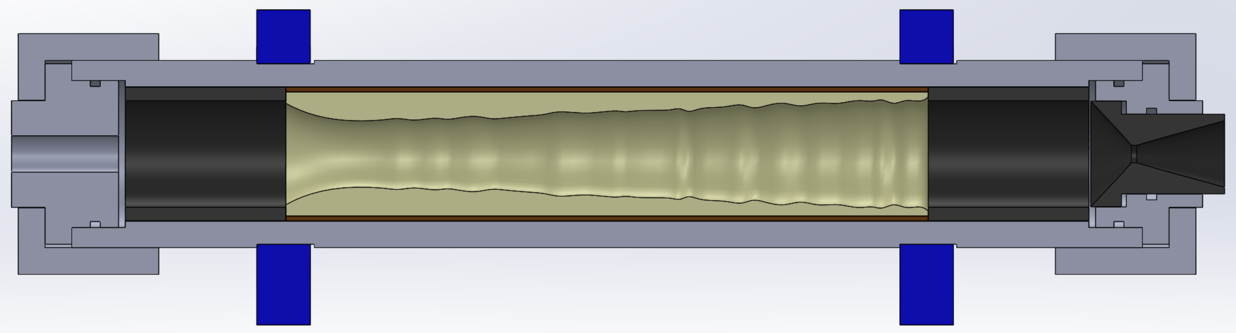
Significance on Field & Society

- Develop more accurate models for solid fuel regression in hybrid rockets.
- Eliminate chlorine containing exhaust gases.
- Safer form of propulsion for human payloads.

ACEL Large Hybrid Motor Pre-Fire Diagram



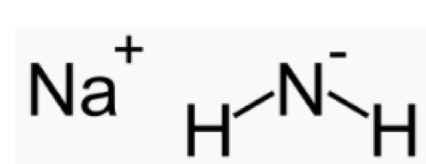
ACEL Large Hybrid Motor Post-Fire Diagram



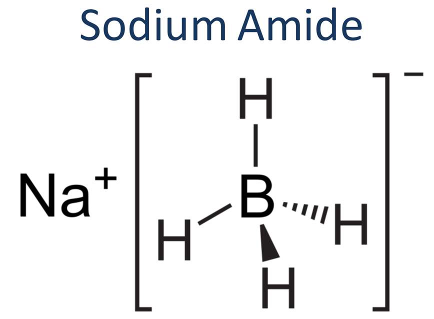
Hot-Fire Test of Paraffin-Based Fuel with Additive

Solid Fuel Additive Selection

- Sodium amide and potassium borohydride release flammable gases when decomposed via heat and/or water.
- Additives have higher density than paraffin wax, increase the total fuel density and density Isp of the system.
- Gas production could increase agitation under the liquid paraffin layer, causing better entrainment of fuel and regression.



Sodium Amide



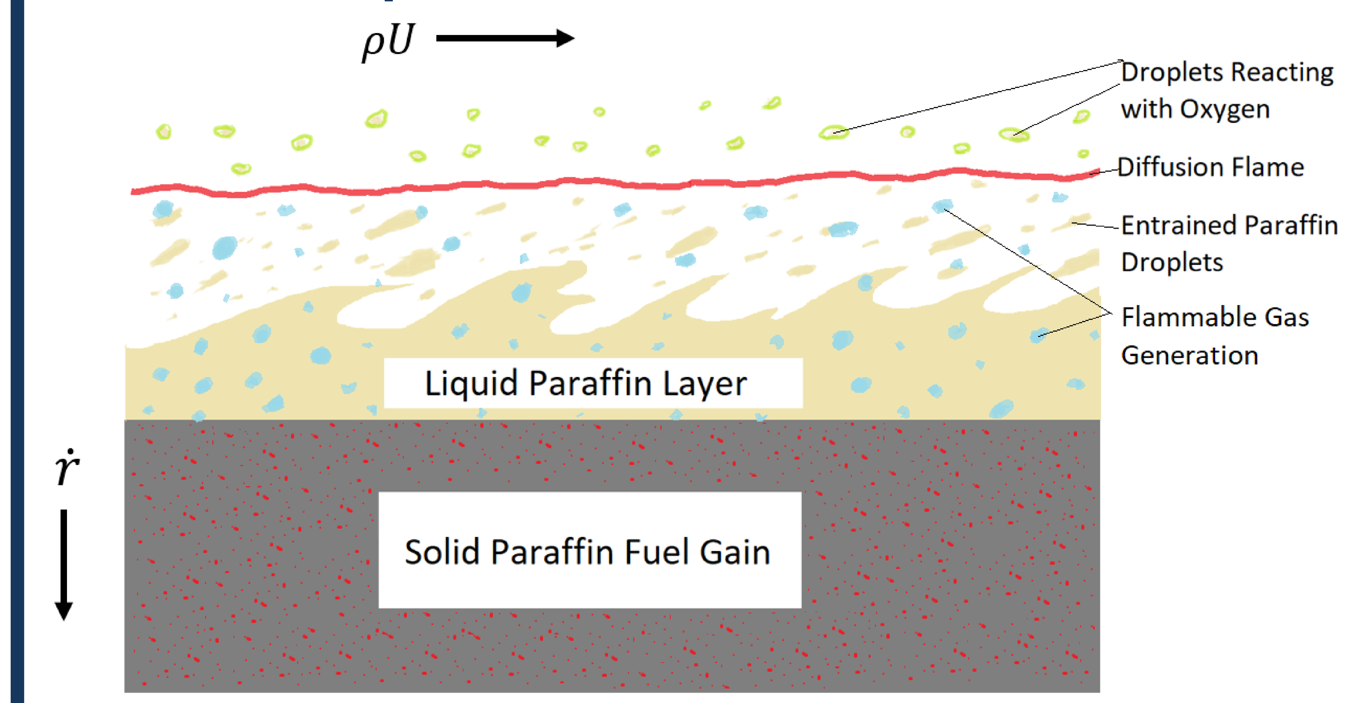
Potassium Borohydride

Governing Equations of Regression

$$G_{ox}(x,t) = \frac{\dot{m}_{ox}}{A_{cs}(x,t)} \qquad G_{total}(x,t) = \frac{\dot{m}_{ox} + \dot{m}_{fuel}(x,t)}{A_{cs}(x,t)} \qquad r_b = a_0 {G_{ox}}^n$$

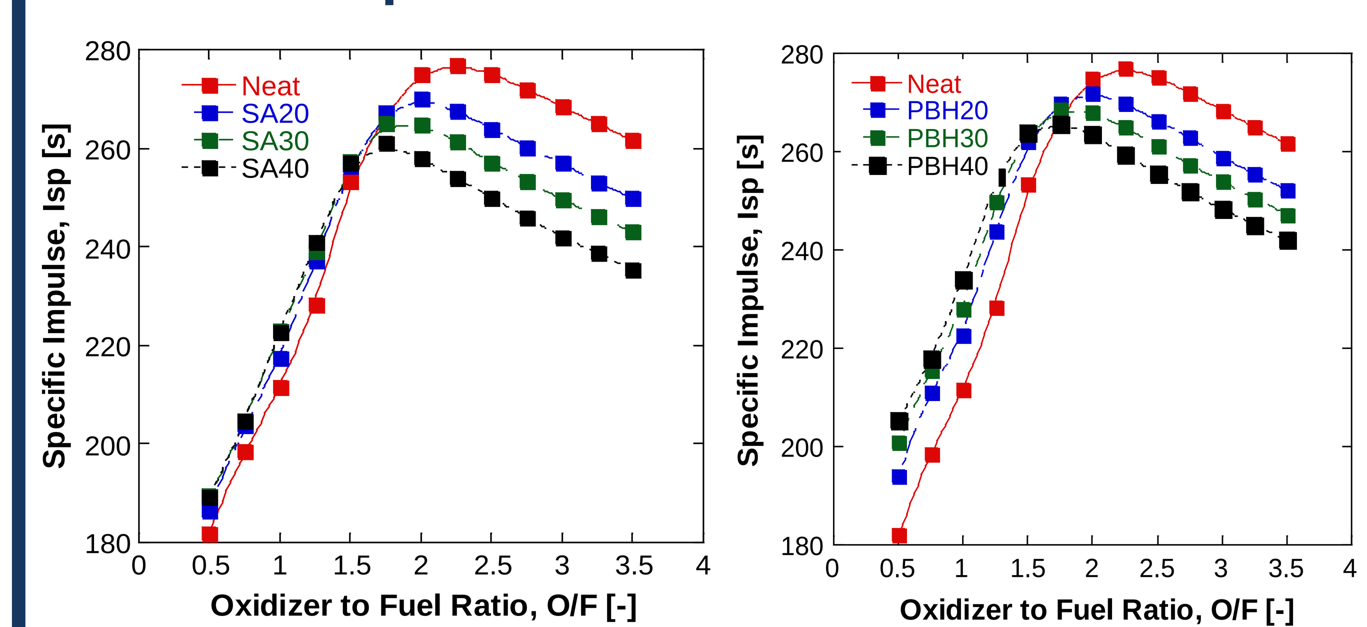
- Regression rate is proportional to the total mass flow rates of oxidizer and fuel per unit port area, known as flux (G_{total}).
- $\mathbf{G_{ox}}$ is the total flux of O_2 and $\mathbf{G_{total}}$ is the both mass flow rates of O_2 and burned fuel per unit port area.
- Regression rate changes with time and axial location as the fuel burns. When the fuel burns, the port area of the fuel increase and lowers the flux, hence the decrease in regression rate.

Liquid Paraffin Entrainment



- Heat from the diffusion flame melts the paraffin wax and it is turned into droplets due to the bulk oxygen flow.
- These droplets react with the oxygen in the oxygen flow down the center port of the fuel grain.
- Smaller droplets have enough time inside the combustion chamber to react completely with the oxygen, where larger droplets may be swept out of the engine, decreasing efficiencies.
- Sodium amide and potassium borohydride may cause increased agitation due to gas generation under the liquid paraffin fuel layer, producing smaller droplets of wax.

Liquid Paraffin Entrainment

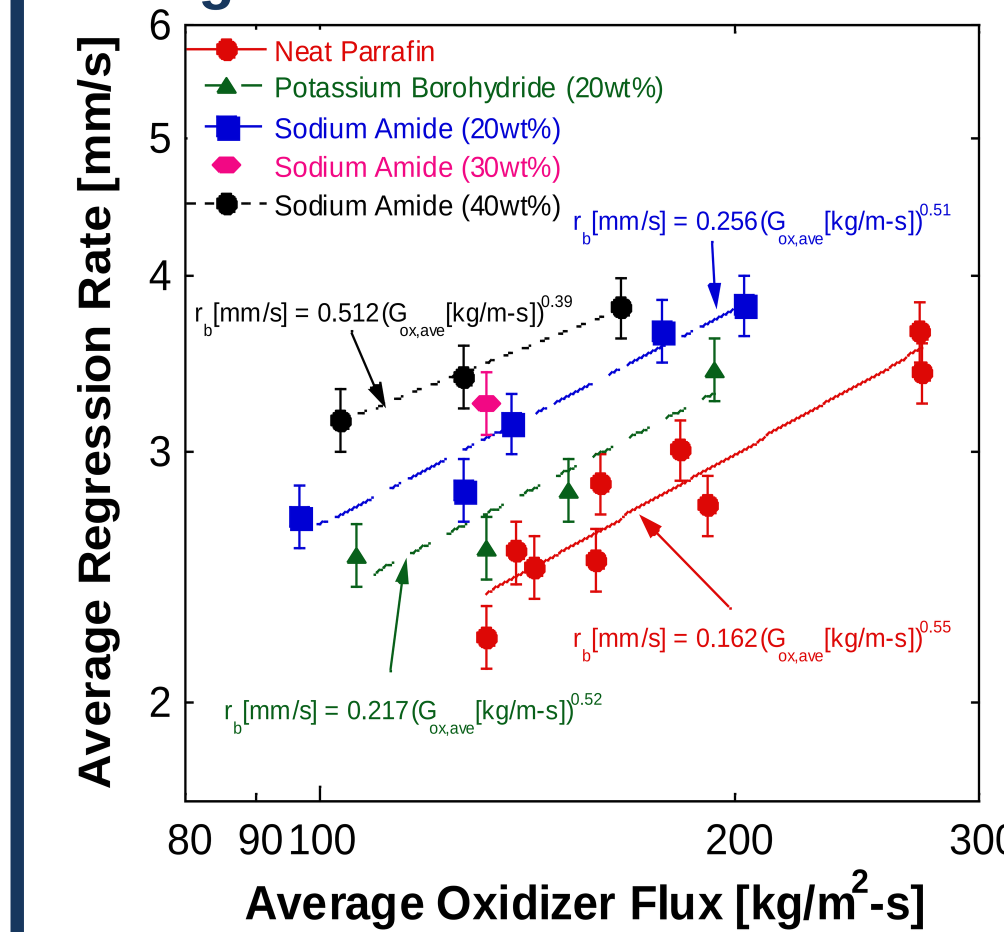


- An increase in Isp was observed at lower oxidizer to fuel ratios (O/F) for potassium borohydride and sodium amide through theoretical calculations using NASA CEA-2000.
- This increases the vehicles throttle limit while maintaining higher levels of Isp with low throttle limits.
- Low throttling decreases oxidizer flowrate, lowers the O/F.
- A shift of peak performance Isp was also observed for both additives, indicating higher Isp for fuel-rich conditions.
- This means a vehicle could carry less oxidizer, saving in total vehicle mass and total volume of oxidizer tanks.

Experimental Operation Conditions

Fuel – Paraffin Wax (C25H52)
Oxidizer – Gaseous Oxygen (GO2)
Chamber Pressure – 3.55 MPa
Thrust Level – 133 – 423 N
Temperature – 2,000 - 2,500 K

Regression Data of Additives



- Additives increased regression rate of fuel.
- Sodium amide showed higher regression compared to potassium borohydride at the same weight percent.
- 20% potassium borohydride = 18% ↑
- 20% sodium amide = 27% ↑
- 40% sodium amide = 46% ↑

Results and Conclusion

- Sodium amide and potassium borohydride both increased regression rate when added to paraffin wax fuel.
- Sodium amide produced higher chamber pressures and thrust levels than potassium borohydride due to increase in regression and higher mass burning rates of fuel.
- Potassium borohydride showed better combustion efficiencies than sodium amide.
- Increasing the weight percent of sodium amide increased regression rate, thrust, and chamber pressure but decreased Isp.

Future Work

- Wider range of weight percent additives.
- Test other metal hydride additives and high energy materials in paraffin wax.
- Test paraffin fuels with additives in an optical hybrid rocket engine.

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