Effect of Fuel-to-Oxidiser Ratio on Thrust Generation of a Hybrid Al + NaOH + H₂O Propulsion System for CubeSat Applications

Ahmed, O. D. and Knoll, A. K.
Surrey Space Centre, University of Surrey,
GU2 7XH, United Kingdom
o.ahmed@surrey.ac.uk

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ABSTRACT

The effect of fuel to oxidiser ratio on the thrust performance of a novel CubeSat propulsion system is presented in this paper. This propulsion system uses aluminium wool as fuel and a mixture of water and sodium hydroxide as oxidiser. The goal of the experiment is to determine the effect of fuel to oxidiser ratio on the thrust profile of the device, as measured with a pendulum type thrust balance in a vacuum chamber facility. Experimental results show that a low fuel to oxidiser ratio reduces the propulsion efficiency and does not support multiple injections. A peak thrust value of 0.032 N was recorded with a specific impulse of 45 s. Based on this specific impulse the anticipated delta-V for a 1U CubeSat of 1.33 kg is 80 m/s, assuming a dry mass ratio of 83.33%.

1. INTRODUCTION

CubeSats are gaining enormous popularity amongst universities, governmental organizations and commercial companies for applications in earth observation, scientific and experimental demonstrations, surveillance, global positioning, and communication [1, 2]. This surge in CubeSat activity is brought about primarily by the substantial reduction in the design, build and launching costs of these satellites compared to a conventional Low Earth Orbiting platforms [3, 4]. One key limitation to CubeSats is the availability of miniaturized propulsion systems that would enable the spacecraft to undertake complex missions involving orbit change, formation flight, and rendezvous and docking. The scaling of conventional propulsion systems to the size and power limitations of CubeSats is not trivial, and requires the investigation of alternative approaches [5-10]. In view of this, a hybrid propulsion system is proposed with a novel combination of chemical propellants (Al + NaOH + H₂O). This selection of propellants was motivated by the fact that they are non-hazardous, cheap, and readily accessible materials, which are important considerations for the ultra-low budget CubeSat market. The slow exothermic reaction of aluminium wool as fuel and a mixture of sodium hydroxide and water as an oxidiser [11, 12] produces a warm mixture of water vapour and hydrogen gas. The gaseous exhaust products are directed through a converging-diverging nozzle to generate thrust.

2. HYBRID AL+NaOH+H₂O SYSTEM

The propulsion system uses a solid fuel (aluminium wool) and a mixture of water and sodium hydroxide as oxidiser. The choice of aluminium as the fuel is to take the advantage of its high energy density; which is over twice the energy density of gasoline per volume. However, this reaction is inhibited by the formation of passivation layer on the surface of the aluminium. Several methods have been suggested to remove the layer but sodium hydroxide solution has proved to yield more exhaust products than other alkaline solutions [13-15]. The equivalent reaction is shown in Eq. 1.

\[ \text{Al}(s) + 3 \text{H}_2\text{O} \rightarrow \text{Al(OH)}_3 + 1.5 \text{H}_2 \quad (1) \]

This chemical reaction is normally considered for the purpose of generating hydrogen gas at standard temperature and pressure. At elevated temperatures, a large fraction of the energy produced by the reaction is consumed through the phase change of the water from liquid to gas. The heated water vapour and hydrogen gas mixture is expelled through a converging-diverging nozzle to produce thrust. The non-combusting moderate temperature nature of the reaction makes it suitable for CubeSat applications. Unlike other chemical propulsion systems for microsatellites, the propellants are readily available and cheap and can be stored for a long duration without decomposition.
3. EXPERIMENT

The impact of fuel-to-oxidiser ratio on thrust performance of the CubeSat propulsion system was performed within the Surrey Space Centre Pegasus vacuum facility using an inverted pendulum type thrust balance and a reaction chamber. The reaction chamber was 30 cubic centimetres in volume and could hold a maximum of 6 g of fuel. An adapted Swagelok cap and plug was used as the nozzle, with a 0.7 mm throat diameter and a divergence angle of 14 degrees. The reaction chamber and the nozzle are shown in Figure 1 and a schematic diagram of the experimental setup is shown in Figure 2.

The setup consists of a thruster (attached to a moving plate of a thrust stand and stationed in a vacuum chamber), an oxidiser tank, a control reaction volume, two solenoid valves, arduino cards and a computer. The fuel is kept in the reaction chamber, while a known volume of sodium hydroxide water mixture is pushed down from the oxidiser tank by a 1 bar back pressure. The operation of the valves is controlled by the arduino controllers. Before every injection of the oxidiser, a calibration of the thrust stand is done by applying a precise

Figure 1: Reaction chamber and adopted nozzle from Swagelok

Figure 2: Schematic of the experimental setup
force to the balance and measuring the resulting displacement [12]. This process is used to determine the calibration constant to correlate measured displacement with the applied force.

4. RESULTS

Table 1: Experimental data and analysis

<table>
<thead>
<tr>
<th>Expt</th>
<th>Fuel-Al wools (g)</th>
<th>Oxidiser (H₂O+NaOH) (g)</th>
<th>Ratio</th>
<th>Propellant after reaction (g)</th>
<th>Thrust (N)</th>
<th>Total impulse (Ns)</th>
<th>Specific impulse (s)</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Remn'g mass</td>
<td>Exht'd mass</td>
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<td>7.46</td>
<td>1.54</td>
<td>0.032</td>
<td>0.6792</td>
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</table>

The goal of the experiment is to determine the effect of fuel to oxidiser ratio on thrust performance of the propulsion system. The optimum molarity of the sodium hydroxide mixture was established in previous experiments [11, 12], where 12.5 mol/kg concentration gave the highest reaction temperature and pressure. In this experiment four different propellant ratios were considered as shown in Tab. 1 for the investigation. Before each experiment, the vacuum chamber is pumped down to a background pressure of about 0.000002 bar. Various mass ratios of fuel and oxidizer were evaluated in these experiments. The highest mass of the fuel used in the experiment was 6 g, and was limited by the volume of the reaction chamber.
The results of the analysis, in terms of peak thrust, total impulse, and specific impulse, are summarized in Tab. 1. It was found that the specific impulse increased as a function of the fuel to oxidizer ratio; with the highest measured performance at 45 s for a mixing ratio of 2:1. The value of the peak thrust also improved with increasing fuel to oxidizer ratio, reaching a maximum of 0.032 N. Since the total amount of propellant was different for each experimental case, the total impulse is not a useful metric of comparison between these four experiments.

5. CONCLUSION

The purpose of this study was to determine the effect of fuel to oxidizer ratio on the thrust performance of a novel CubeSat propulsion system. The results have shown that lower mass of fuel to higher mass of oxidiser is not desirable as this act to reduce both the peak thrust and average specific impulse. For higher fuel to oxidizer ratios, the performance increases, and also allows for more repeat cycles. This propulsion system has demonstrated a specific impulse of 45 s, which is able to deliver a ΔV of about 80 m/s for a 1U CubeSat of 1.33 kg, assuming a dry mass ratio of 83.33%. Though the propulsion performance is less than many conventional microsatellites propulsion systems [16], it is simple to build and does not place power demand on the microsatellites. The propellants are cheap, storable, non-toxic and the reaction occurs at a moderate temperature.

ACKNOWLEDGEMENT

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6. REFERENCES


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