Combustion performance with ap and boron addition in staged hybrid rocket

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Abstract. This study investigated the effect of ammonium perchlorate (AP) and boron addition on controllability of the combustion temperature in fuel-rich effluent and system specific impulse. In addition, a series of combustion tests was carried out to analyse and evaluate the effect of boron addition on fuel regression rate and radial temperature profiles. To keep the hybrid rocket engine advantages, upper limit of AP and boron contents in solid fuel was set to be 15 and 10wt% respectively. The results suggested that AP addition proved to be very effective in controlling the effluent temperature. Not only that, it also offers less injected oxidizer mass flow, and resulted in less O/F variation, and less combustion pressure while producing the same combustion in temperature fuel-rich effluent. With boron addition, it also provided more uniform radial temperature distribution. Also, boron addition increased specific impulse by 6.8-13.7%. Secondary combustion using different solid fuels showed a decrease in c* efficiency with increasing boron content in solid fuel. Combustor length and combustion pressure were introduced to improve the combustion of boron particles, however, combustion efficiency was decreased with increasing combustion pressure and combustor length for given test conditions.

1. Introduction
A staged hybrid rocket engine (HRE) is a new concept of HRE consisted with gas generator and secondary combustor [1]. The distinctive feature of the staged HRE is to minimize the losses of combustion performance that occurs with the oxidizer-to-fuel (O/F) shifting, while keeping the essential advantages of HRE. The gas generator (GG) as a primary combustor generates fuel-rich effluent utilizing solid fuel and gas oxidizer, which is then expelled and mixed with additional aft-injected secondary oxidizer in the secondary combustor for thrust generation. A schematic of staged HRE is shown in figure 1.

![Figure 1. Schematic of staged HRE.](image-url)
The use of oxygen and nitrogen mixture oxidizer is one of techniques to generate fuel-rich effluent that meets the design requirement of GG temperature in staged HRE [1]. Equivalence ratio had increased significantly with decreasing oxygen (O₂) content (by volume) in the mixture oxidizer, resulting in the substantial decrease in the effluent temperature. In the results, with the use of hydroxyl-terminated polybutadiene (HTPB) and 28% oxygen content mixture oxidizer, the fuel-rich effluent with a temperature of 1290 K was successfully produced, which was in the range of the design requirement of GG. However, a loss of \( I_{sp} \) (specific impulse) performance was inevitable due to the deliberate decrease in oxygen content of mixture oxidizer, which used for the GG combustion, as shown in figure 2. Though the staged HRE offers many advantages, its performance of \( I_{sp} \) needs to be improved at least as comparable as conventional chemical rockets to outweigh its advantages.

Meanwhile, the use of metal additives to solid fuel is one of the common methods to improve the \( I_{sp} \) performance as well as fuel density [2-4]. And, boron (B) is one of the most attractive candidates, as it is reported to have the highest combustion enthalpy per mass and volume [4, 5]. Hence, with metal additives (e.g., boron) in staged HRE, an enhancement of \( I_{sp} \) performance is expected and therefore possibly it can be competitive with other chemical rockets. However, several issues must be resolved in order to maximize the benefit with boron addition. First, the loading limit of boron in solid fuel should be carefully chosen to avoid possible combustion instability. In this regard, Evans [6] examined the detail of regression rate behaviour of HTPB and boron-added solid fuels in hybrid rockets, and reported that a loading of 13wt% (by weight) of boron addition demonstrated a limit of stable combustion. Second, the difficulties associated with ignition and efficient combustion should be resolved to realize the energetic potential [6-9]. Foelsche [5] investigated boron particle ignition and combustion. And they reported a regenerating protective oxide coating hinders that boron ignition. In addition, boron particle ignition is highly dependent on the chamber pressure, particle size and combustion temperature [5]. Haddad [10] found that introduction of aft-combustion chamber, where fuel-rich effluent products are mixed with cold bypass oxidizer, is an effective approach to improve the combustion of boron. Miyayama [11] studied combustion of boron particles in a ducted rocket, and reported that use of minute particles is one method to increase the combustion efficiency in the secondary (ramjet) combustor. They found that combustion efficiency is increased by 7–9% with the addition of 20wt% fine particles [11].

The addition of AP is expected to provide a better controllability on the effluent temperature and the addition of boron is able to compensate the overall system \( I_{sp} \) loss by increasing combustion temperature in secondary combustor. This study investigated the effect of AP and boron addition on the combustion in hybrid GG as this component produces the fuel (i.e., fuel-rich effluent) for the overall system. Then, based on the experimental results, a theoretical \( I_{sp} \) performance of the overall system was evaluated. Finally, secondary combustion tests were carried out to evaluate the combustion performance. Additionally, this study examined the combustion behavior of boron-added fuels with various chamber pressures, chamber lengths, and equivalence ratio.
2. Design of Combustion Test

A series of combustion tests was firstly conducted with a laboratory-scale hybrid GG, as shown in figure 3. Solenoid and check valves were used to control oxidizer feeding. The oxidizer mass flow rate for was controlled up to 25 g/sec by using the mass flow controller. Nitrogen(N₂) gas was used to purge the combustion by programmable logic controller control. Piezoelectric-type sensors were installed to measure the combustion pressure. A DAQ board and the LabVIEW program were also implemented for the data acquisition process. The dimension of the baseline fuel grain had an outer diameter of 50 mm and an inner diameter of 20 mm. In the baseline configuration, chamber lengths of the main, pre, and post chamber were fixed as 200, 45, and 200 mm, respectively. A water-cooled nozzle was used, in which the throat diameter was 6.5 mm. Ignition was achieved with an A-type model rocket engine, which was first ignited with a small pyrotechnic igniter.

![Figure 3. Gas Generator(GG) and thermocouples in post-chamber.](image)

| Test | Additive, wt% | O/Fstoi | $\dot{m}_{\text{ox}}$/g/sec | O/Fact | $\Phi$ | $T_{\text{Effluent}}$, K |
|------|--------------|---------|-----------------|---------|-------|------------------|
| 1    | None         | 11.35   | 15              | 2.50    | 4.53  | 1290             |
| 2    | (Pure HTPB)  |         | 20              | 2.84    | 3.99  | 1410             |
| 3    |              |         | 25              | 3.09    | 3.67  | 1580             |
| 4    | AP5          | 10.72   | 13              | 2.25    | 4.77  | 1410             |
| 5    |              |         | 15              | 2.44    | 4.39  | 1520             |
| 6    |              |         | 20              | 2.73    | 3.92  | 1660             |
| 7    |              |         | 10              | 1.89    | 5.34  | 1400             |
| 8    | AP10         | 10.09   | 15              | 2.31    | 4.37  | 1570             |
| 9    |              |         | 20              | 2.56    | 3.93  | 1780             |
| 10   | AP15         | 9.46    | 8               | 1.57    | 6.03  | 1390             |
| 11   |              |         | 10              | 1.82    | 5.19  | 1550             |
| 12   |              |         | 12              | 1.89    | 5.00  | 1680             |
| 13   |              |         | 15              | 2.24    | 4.22  | 1770             |
| 14   | AP10/B5      | 9.92    | 11              | 2.08    | 4.73  | 1460             |
| 15   |              |         | 16              | 2.33    | 4.21  | 1590             |
| 16   |              |         | 20              | 2.71    | 3.63  | 1750             |
| 17   | AP10/B10     | 9.75    | 10              | 1.78    | 5.49  | 1570             |
| 18   |              |         | 15              | 2.23    | 4.37  | 1800             |

Table 1. Summary of test results of GG combustion.

The NASA CEA(Chemical Equilibrium and Application) program was used to calculate the theoretical oxidizer-to-fuel ratio (O/Fstoi) for each test case. The actual O/F ratio (O/Fact) was calculated with the total mass of injected oxidizer divided by the total burned fuel mass during burning time. Then, the equivalence ratio was calculated with the ratio of O/Fstoi to O/Fact. The regression rate
was determined at each test with the space-time averaged method. For temperature measurements, seven exposed K and R-type thermocouples were used in all cases, which were located at specific axial and radial locations in the post chamber, as shown in figure 3.

3. Results and Discussion

3.1. Gas Generator Combustion. A series of combustion tests was done with variation of AP and boron contents at different oxidizer mass flux ranges to investigate the combustion characteristics in hybrid GG of staged HRE. Table 1 shows the summary of test results. For a baseline case, HTPB and mixture oxidizer of 28% oxygen content was chosen, as this combination meets the hybrid GG requirement [1]. Figure 4 shows the effect of AP and boron in solid fuel on regression rate of HTPB with GOX and 28% oxygen content mixture oxidizer. To validate the data, regression rate of HTPB with GOX test was compared to current test data, and showed a good agreement [1]. Additionally, to validate the AP effect on the regression rate, regression rate of HTPB with 7.55 wt% AP was plotted and showed fairly good agreement with current data.

Figure 5 shows the regression rate of HTPB with variation of AP and boron contents. As expected, regression rate increased with increasing AP content. Since the given weight of solid fuel is substituted with AP oxidizer, this could lead to the partial reduction of the total amount of oxidizer supply from the head-end injector. AP10/B5 fuel showed a very similar regression rate compared to that of pure HTPB fuel. However, when compared to the regression rate of AP10, regression rate decreased. This was most likely due to the difficulties associated with ignition and combustion of boron particles reported by Thomas [8].

3.1.1. Effluent temperature. Figure 6 shows effluent temperature against equivalence ratio with AP and boron content variation. Generally, effluent temperature was decreased with increasing equivalence ratio. However, effluent temperature had increased from 1290 to 1400 K though the equivalence ratio increased from 4.53 (pure HTPB fuel) to 5.34 (AP10 fuel) with increasing AP content in solid fuel. Unlike pure oxygen, combustion with AP can release significant amount of heats during chemical reactions. And this could be the reason for higher combustion temperature even with higher equivalence ratio. As for the AP10/B5 solid fuel, it was expected to have even higher effluent temperature compared to AP10 fuel due to high-energy release of boron combustion. However, results showed that AP10/B5 had a performance in between that of the pure HTPB and AP10 fuels. And this seems due to the difficulties in ignition and efficient combustion with boron addition. Foelsche [5] reported that boron ignition delays were reduced with increased pressure, decreased particle size, and increased temperature. However, as the current study is focused on the hybrid GG, in which GG combustion is used to generate fuel-rich effluent of a temperature around 1300 K, the difficulties associated with boron was inevitable.
3.1.2. **Radial temperature profile.** As for the GG, it would be necessary to produce fuel-rich effluent with a good radial temperature profile for improving combustion efficiency in a secondary combustor and overall system performance [1]. However, because of the diffusional nature of combustion in a hybrid GG, the radial variation of fuel-rich effluent temperatures seems to be inevitable. Temperature measurements of the test with HTPB fuel are shown in figure 7a). The maximum temperature is found at location 7 and the minimum at location 4. Higher temperatures are measured at the downstream, since unburned fuels are continuously burning as they pass through the post chamber. The radial temperature profile of AP10/B5 is shown figure 7b). As shown, AP10/B5 fuel showed an almost half of the temperature variation reported by the pure HTPB fuel case. These results could be mainly due to improved mixing performance with AP and boron additions. Hence, better combustion performance can be expected with boron added solid fuel.

3.2. **Secondary Combustion**

3.2.1. **Theoretical Vacuum Specific Impulse.** Vacuum specific impulse is a measure of the efficiency of the overall engine (i.e., staged HRE) performance. Even the addition of boron to solid fuel can produce better radial temperature profiles; the most significant benefit acquired from boron addition is the increase in overall system $I_{sp}$ performance. Thus, the addition of boron can compensate for the loss of $I_{sp}$ due to the use of mixture oxidizer in the GG. Figure 8 presents the estimations of overall $I_{sp}$ performance of various fuels (i.e., fuel-rich effluent) with respect to the engine OF ratio by using the NASA CEA code. The estimation was done at the chamber pressure and expansion ratio of 1000 psi (6.89 MPa) and 10, respectively. As for the boron added fuels, peak value of $I_{sp}$ increased about 6.8% (AP10/B5), 13.7% (AP10/B10) compared to that of pure HTPB. Results also suggested that the peak values of $I_{sp}$ increase up to about 2.8% with AP addition (AP10) when compared to that of pure HTPB fuel. Note that the current study is done only with fuels of 10wt% AP and 10 wt% boron additions. Thus, the increase in AP weight from 10% and boron weight from 10% can bring about a further increase in peaks of $I_{sp}$, making up for substantial drops of $I_{sp}$ in the overall system due to the use of mixture oxidizer in the GG.
Figure 6. Effluent temperature with respect to equivalence ratio.

Figure 7. Radial temperature profile of Test with a) HTPB and b) AP10/B5.

Figure 8. Overall system vacuum $I_{sp}$ performance versus O/F ratio (oxidizer: LOX, fuel: fuel-rich effluent).

Figure 9. Staged HRE assembly and injector design.
Table 2. Sequence of test operation.

| Action                | Timeline, sec |
|-----------------------|---------------|
| Mixture oxidizer on   | 0.0           |
| Ignitor on/off        | 1.0           |
| (Only hybrid GG is operating) | (1.0 - 4.0) |
| GOX oxidizer on       | 4.0           |
| (Entire staged HRE is operating) | (4.0 – 8.0) |
| Mixture oxidizer off  | 8.0           |
| GOX oxidizer off      | 8.0           |
| N₂ gas on             | 8.0           |
| N₂ gas off            | 10.0          |

3.2.2. Sequence of staged combustion. Additional tests were carried out to assess the suitability of the effluent and to investigate the sequence of each event in staged combustion. One of the key requirements of the effluent is the ignition capability in the secondary combustor. Lee [1] reported that the effluent temperature was maintained relatively low to allow the use of low-temperature tolerant materials for the hybrid GG. However, it was important for the effluent to maintain a high enough temperature to initiate the combustion in the secondary combustor when additional oxidizer was injected. The entire staged HRE assembly is shown in figure 9. In the baseline configuration, chamber lengths of pre, hybrid GG, and secondary were 45, 400, and 200 mm, respectively.

Figure 10. Snapshot of staged combustion at a) 2, b) 4, and c) 7 seconds of test operation.
As this test is the first attempt to test the staged combustion of staged HRE, the amount of GOX injected into the secondary combustor was intentionally increased from the stoichiometric value for the fuel-lean combustion in order to decrease the engine performance. Table 2 shows a test sequence done in this test. As shown, only the hybrid GG was operated from 1.0 to 4.0 sec of the period. Then, GOX was injected into the secondary combustor for the next 4 sec. As soon as GOX was additional injected to the secondary combustor, spontaneous ignition was achieved. Figure 10a), b), and c) shows the snapshot of staged combustion at 2, 4, and 7 sec of test operation, respectively. Based on the test results, an effluent temperature as low as 1290 K was confirmed to be high enough to initiate spontaneous ignition when additional oxidizer was injected to the secondary combustor. Figure 11 shows a pressure trace of GG and secondary combustor.

3.2.3. Fuel type. In order to examine the combustion performance of different fuels, combustion efficiency based on characteristic velocity ($\eta_{c*}$) was selected as a mean of indication. For the characteristic velocity, the definition given in Eq. (1) was used.

$$c_{exp}^* = \frac{P_t A_t C_{dt}}{m_f + m_{ox}}$$

Here, $P_t$ is chamber pressure in Pa, $A_t$ is nozzle throat area in m$^2$, $m_f$ is mass flow rate of effluent in kg/s, $m_{ox}$ is mass flow rate of oxidizer in kg/s and $C_{dt}$ is discharge coefficient at nozzle throat which was assumed to be 1.0. Then, the combustion efficiency based on characteristic velocity was calculated by using the following definition.

$$\eta_{c*} = \frac{c_{exp}^*}{c_{th}^*}$$

where, $c_{exp}^*$ is experimental characteristic velocity in m/s and $c_{th}^*$ is theoretical characteristic velocity. The theoretical characteristic velocity was calculated using the CEA at the appropriate operating conditions, such as pressure and compositions of fuel and oxidizer. Also, injector type was directly adopted from the reference [12], as it showed the best combustion performance among the tested injector types, which have injection angle of 30 deg., effluent (fuel) port diameter of 4.7 mm, gap diameter of 10.7 mm, and oxidizer port diameter of 18.5 mm. A detailed configuration can be found in reference [12].

Table 3 shows the summary of test conditions and results of secondary combustion. To maintain the GG combustion pressure relatively constant, 1st oxidizer mass flow rate was fixed to 15 g/sec. Since theoretical characteristic velocity is strongly dependent on equivalence ratio, comparisons between $c^*$ efficiencies of different fuels are performed at very similar equivalence ratios by controlling only the 2nd oxidizer mass flow rate. As shown in the table, all tests were showed to have equivalence ratio range from 0.45 to 0.66. Figure 12 shows the $c^*$ efficiency of different fuels (test 1-8). Based on the results, pure HTPB fuel showed the highest combustion performance among the tested fuels, which has the maximum $c^*$ efficiency of 91.7 % (test 2). AP10 fuel showed a very similar performance compared to pure HTPB test cases. However, with increasing boron content, $c^*$ efficiency decreased to as low as 61.2% (test 8). This was most likely due to the difficulties associated with ignition and combustion of boron particles reported by numerous references regarding boron combustion [4-11, 13].
3.2.4. Nozzle throat diameter and Combustor length. Though boron addition showed an impressive increment in theoretical combustion performance, realizing such potential was challenging. Hence, other approaches were needed to improve the ignition and combustion of boron particles in secondary combustor. Hence, literature survey was done with a goal to find an effective approach to improve the boron combustion. Foelsche [5] reported that combustion time of boron particles decreased with increasing combustion pressure. Haddad [10] reported that use of aft-burner is an approach to improve the boron combustion efficiency. Kuwahara [13] studied ducted rocket with boron added propellant, and reported that effective use of recirculation zone results to increased combustion efficiency. In addition, Miyayama [11] reported that combustion efficiency increased by 7~9% with the addition of 20 wt% Mg or Zr along with boron.

Among the reviewed approaches, combustion pressure, to decrease the combustion time, and combustor length, to increase the residence time, were chosen for this study. Figure 13 shows the test results. As shown, an increased combustion pressure (by decreasing nozzle throat diameter) did not result to improvement of c* efficiency. As for the combustor length variation test, the results rather showed a decreased c* efficiency compared to the baseline case. This proved that an increment of combustion pressure from 75.9-79.0 to 129.6-135.4 psi and of combustor length from 200 to 300 mm were not effective enough to influence the combustion of boron particles within the test conditions and configurations used in the present study.

4. Conclusions

This study conducted a series of combustion tests with boron addition to solid fuels to understand the effect of boron addition on the GG combustion, theoretical specific impulse, and combustion performance of secondary combustor. Loading weight of was limited in order to retain the HRE advantages and to prevent possible reported effects, and therefore boron content of 10wt% were used in this study.

In GG combustion, an addition of boron did not show much of differences with respect to regression rate and effluent temperature compared to 10wt% AP solid fuel. However, the results showed that the addition of boron tended to provide more uniform radial temperature distribution. Based on GG combustion test results, theoretical performance was calculated. In results, 5wt% boron addition showed 6.8% increase in $I_p$ performance compared to pure HTPB fuel case, and 10wt% boron showed 13.7% increment. Considering this study was done with only case of boron content up to 10wt%, further enhancement in $I_p$ could be expected with higher boron content.

Secondary combustion tests were conducted to compare the combustion performance of different fuels. As rather expected, fuel contacting boron showed a decreased c* efficacy compared to the baseline cases. This study also conducted tests with combustion pressure and combustor length.
variations, but no noticeably increment in combustion performance was observed. Rather, $c^*$
efficiency decreased with increasing pressure and combustion length. Future studies will carry out
more combustion tests with other reported approaches to improve the combustion of boron and
thereby to maximize the energetic potential of boron.

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