Combustion Performance of a Staged Hybrid Rocket with Boron addition

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Abstract. In this paper, the effect of boron on overall system specific impulse was investigated. Additionally, a series of combustion tests was carried out to analyze and evaluate the effect of boron addition on O/F variation and radial temperature profiles. To maintain the hybrid rocket engine advantages, upper limit of boron contents in solid fuel was set to be 10 wt%. The results also suggested that, when adding boron to solid fuel, it helped to provide more uniform radial temperature distribution and also to increase specific impulse by 3.2%.

1. Introduction

Staged hybrid rocket engine (HRE) is a newly introduced concept of HRE by the recent study. It can minimize the loss of combustion performance with the oxidizer-to-fuel (O/F) shifting, while maintaining the key advantages of HRE. It uses the hybrid gas generator (GG) as a primary combustor, which utilizes solid fuel and gas/liquid oxidizer to produce fuel-rich effluent, which is then expelled and mixed with additional aft-injected secondary oxidizer in the secondary combustor for thrust generation.

The use of oxygen and nitrogen mixture oxidizer is one of techniques to generate fuel-rich effluent that meets the design requirement of GG. Equivalence ratio had increased significantly with decreasing oxygen (O2) content (by volume) in the mixture oxidizer, resulting in 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 Isp (specific impulse) was inevitable due to deliberately decreased oxygen content in mixture oxidizer. Though the staged HRE offers many advantages, its Isp should be improved to be at least competitive with conventional chemical rockets to outweigh its advantages.

At the same time, several technical issues can be resolved. One of issues is the low Isp(specific impulse) of overall system. A loss of overall system Isp was inevitable due to deliberately decreased oxygen content in mixture oxidizer [1]. Though the staged HRE offers many advantages such as; minimized performance variation with respect to O/F shifting and engine stop-restart ability, Isp performance of overall system should be improved to be at least competitive with conventional chemical rockets to outweigh its advantages.

Meanwhile, an addition of metal additives to solid fuel is widely used technique to improve the Isp performance as well as fuel density [6-8]. Hence, with use of metal additives in staged HRE, this could bring an enhancement of Isp performance and therefore possibly be competitive with other chemical rockets with respect to Isp performance. However, loading limit of metal additives in solid fuel should be carefully chosen for possible combustion instability. In this regard, Evans [9] examined a detailed
regression rate behavior of HTPB and metalized solid fuels in hybrid rockets, and reported that a loading of 13 wt% of metal additives demonstrated a limit of stable combustion. As this is likely to be the first attempt to study the effect of metal additive in hybrid GG, this study has limited metal additives content up to 5 wt%. For a current study, boron (B) was used as a metal additive, as it is reported to have the highest combustion enthalpy per mass and volume [8, 10]. However, according to many literatures related to boron metal additives, its implementation in HRE has been limited due to difficulties associated with ignition and efficient combustion [10-13]. Foelsche [10] studied boron particle ignition and combustion, and reported that boron ignition is hindered by a regenerating protective oxide coating. And, boron particle ignition is highly dependent on the chamber pressure, particle size and combustion temperature [10]. Also, Shin [13] reported a problem associated with a curing reaction during manufacturing process of boron added HTPB solid fuel. In this study, boron bead, which is a mixture of PMMA (PloyMethyl MethAcrylate), AP and boron, was adopted from Shin [13], with an only intention to prevent the curing reaction, not to increase the pressure exponent as intended by the reference. A detailed development process and its compositions of boron bead are described in reference [13].

The key purpose of boron addition is to compensate the Isp loss; therefore, the main objective of this study is to determine if an improvement in Isp is possible with the addition of boron. Additionally, a series of experimental tests was carried out to investigate the combustion characteristics with additives in hybrid GG such as; O/F variation and radial temperature profiles. Also, based on the results, an experimental evaluation of the beneficial effects of each additive were presented.

2. Design of combustion test
A series of combustion tests was conducted with a laboratory-scale HRE, as shown in Fig. 2. Solenoid and check valves were used to control oxidizer feeding. The oxidizer mass flow rate for was controlled up to 25 g/s 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.

The NASA CEA (Chemical Equilibrium and Application) program was used to calculate the theoretical oxidizer-to-fuel ratio (O/F_{tho}) for each test case. The actual O/F ratio (O/F_{aco}) 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/F_{tho} to O/F_{aco}. 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 Fig. 2.
To quantify the O/F variation, the initial and final O/F (O/F$_{ini}$ and O/F$_{fin}$) were calculated based on the expressions suggested by Karabeyoglu et al. [14]. Since the O/F variation was highly dependent on the oxidizer flux, $G_ox$, and exponent $n$, a study was focused on O/F behavior with respect to those parameters. In the literature, the classical HRE was reported to have an O/F variation as high as 1.17, meaning the O/F increased by 17% from the initial value [15]. A detailed explanation can be found in reference [1].

![Diagram of HRE assembly and location of thermocouples in post-chamber]

### 3. Results and Discussions

#### Table 1. Summary of test results in GG combustion

| Test | Additive | $\text{O/F}_{\text{sto}}$ | $\dot{m}_{\text{react}}$, g/sec | $\text{O/F}_{\text{act}}$ | $\Phi$ | $T_{\text{Effluent}}, \text{K}$ | $\text{O/F}$ variation | $a$ | $n$ |
|------|----------|----------------|------------------|-----------------|---|--------------|-------------------|---|---|
| 1    | None (HTPB) | 11.35 | 15 | 2.50 | 4.53 | 1290 | 1.04 | 0.03 | 0.59 |
| 2    | None (HTPB) | 11.35 | 20 | 2.84 | 3.99 | 1410 | 1.05 | 0.03 | 0.59 |
| 3    | None (HTPB) | 11.35 | 25 | 3.09 | 3.67 | 1580 | 1.05 | 0.03 | 0.59 |
| 4    | AP10     | 10.09 | 10 | 1.89 | 5.34 | 1400 | 1.02 | 0.03 | 0.56 |
| 5    | AP10     | 10.09 | 16 | 2.31 | 4.37 | 1570 | 1.02 | 0.03 | 0.56 |
| 6    | AP10     | 10.09 | 20 | 2.56 | 3.93 | 1780 | 1.03 | 0.03 | 0.56 |
| 7    | AP10/B5  | 9.92  | 11 | 2.08 | 4.78 | 1460 | 1.03 | 0.03 | 0.57 |
| 8    | AP10/B5  | 9.92  | 16 | 2.33 | 4.25 | 1590 | 1.03 | 0.03 | 0.57 |
| 9    | AP10/B10 | 9.75  | 20 | 2.71 | 3.66 | 1750 | 1.03 | 0.03 | 0.57 |
| 10   | AP10/B10 | 9.75  | 10 | 1.78 | 5.49 | 1570 | - | 0.05 | 0.44 |
| 11   | AP10/B10 | 9.75  | 15 | 2.23 | 4.37 | 1800 | - | 0.05 | 0.44 |

#### 3.1. Effect of boron addition on Isp performance

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 HTPB fuel is presented in Fig. 3a). 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 Fig. 3b. 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.

![Radial temperature profile of Test a) HTPB and b) AP10/B5](image)

**Fig 3. Radial temperature profile of Test a) HTPB and b) AP10/B5**

### 3.2. Effect of boron addition on Isp performance

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 Isp performance. Thus, the addition of boron can compensate for the loss of Isp due to the use of mixture oxidizer in the GG. Fig. 4 presents the estimations of overall Isp performance of various fuels (i.e., fuel-rich effluent) with respect to the engine O/F 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 fuel, peak value of Isp increased about 1.3% compared to that of AP10 fuel and about 3.2% compared to the pure HTPB fuel case. Results also suggested that the peak values of Isp increase up to about 2.8% with AP addition (AP15 fuel) when compared to that of pure HTPB fuel. Note that the current study is done only with fuels of 15 wt% AP and 5 wt% boron additions. Thus, the increase in AP weight
from 15% and boron weight from 5% can bring about a further increase in peaks of Isp, making up for substantial drops of Isp in the overall system due to the use of mixture oxidizer in the GG. Also, Lee [1] reported that overall system Isp performance could be increased with decreasing effluent temperature. Since current analysis was done at an effluent temperature of around 1430 K, further increment in Isp could be expected with lower effluent temperature that meets the requirement of hybrid GG (below 1300 K). Considering that the HRE has Isp of around ~310 sec for classical [6], and ~320 sec for solid propellant GG [5], it would be possible to make staged HRE to be comparable to other chemical rockets, if higher contents of additives were used as well as optimization in effluent temperature.

**Fig 4. Overall system vacuum Isp performance versus O/F ratio (oxidizer: LOX, fuel: fuel-rich effluent)**

3.3. **Secondary combustion**

Additional tests were carried out to assess the suitability of the effluent and to investigate the sequencing of events in staged combustion. One of the key components of the effluent was the ignition capability in the secondary combustor, and this was the focus of these tests. 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 Fig. 5. In the configuration, chamber lengths of pre, hybrid GG, and secondary were fixed at 45, 400, and 200 mm, respectively.

**Table 2. Sequence of test operation**

| Action               | Timeline, sec |
|----------------------|--------------|
| Mixture oxidizer on  | 0.0          |

**Fig 5. Staged HRE assembly and injector design**
Since the goal was to investigate whether the effluent temperature was high enough to guarantee spontaneous ignition, and to test the sequence of staged operation, tests were conducted with a large nozzle throat area to prevent any possible nozzle blockage. The coaxial-type injector was used, which had inner, outer, and annulus diameters of 4.7, 10.7, and 21.5 mm, respectively. The test 2 condition was used to simulate the effluent coming out from the hybrid GG, and GOX was used as the aft-injected oxidizer. 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 6.0 sec of the period. Then, GOX was injected into the secondary combustor for the next 5 sec. As soon as GOX was additional injected to the secondary combustor, spontaneous ignition was achieved. Fig. 6a), b), and c) shows the snapshot of staged combustion at 2, 7, and 10 sec of test operation, respectively. Based on the test results, an effluent temperature of 1410 K was confirmed to be high enough to initiate spontaneous ignition when additional oxidizer was injected to the secondary combustor.
In addition, combustion efficiency based on characteristic velocity ($\eta_{c^*}$) was calculated. For the experimental characteristic velocity calculation, the definition given in Eq. (1) was used.

$$c^*_\text{exp} = \frac{P_c A_t C_{th}}{\dot{m}_f + \dot{m}_\text{ox}}$$

(1)

where, $P_c$ is chamber pressure in Pa, $A_t$ is nozzle throat area in m$^2$, $\dot{m}_f$ is mass flow rate of effluent in kg/s, $\dot{m}_\text{ox}$ is mass flow rate of oxidizer in kg/s and $C_{th}$ 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.

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

(2)

where, $c^*_\text{exp}$ is experimental characteristic velocity in m/s and $c^*_\text{th}$ is theoretical characteristic velocity in m/s. The theoretical characteristic velocity was calculated using the CEA at the appropriate operating conditions, such as pressure and compositions of fuel and oxidizer. Finally, combustion efficiency based on characteristic velocity of the tested staged combustion was calculated to be 82%.

For the current stage of research, the optimal configurations and flow conditions for the secondary combustion have not yet been determined. Once the optimization was done, the effluent temperature, which was capable of initiating the secondary combustion, could be decreased, since better mixing between the effluent and the oxidizer would give more potential for the effluent to initiate the secondary combustion. Also, higher combustion efficiency (>90%) in secondary combustor could be expected with the optimization of the secondary combustor.

4. Conclusions or Concluding Remarks

This study conducted a series of combustion tests with AP and boron additives in solid fuels to understand the effect of boron addition on the overall system specific impulse. Though the staged HRE offers many advantages such as; minimized performance variation with respect to O/F shifting and engine stop-restart ability, effluent temperature controllability as well as overall system Isp performance should be improved. Therefore, boron as a metal additive was introduced to investigate its effects on GG combustion characteristics as well as on Isp performance. Loading weight of was limited in order to retain the HRE advantages and to prevent possible reported effects, and therefore boron content of 10 wt% were used in this study. Even though the addition of boron did not show much of differences with respect to regression rate and effluent temperature compared to 10 wt% AP solid fuel, the results showed that the addition of boron tended to provide more uniform radial temperature distribution. More importantly, boron addition showed 3.2% increase in Isp performance compared to pure HTPB fuel case, and 1.3% increase compared to 10 wt% AP solid fuel. Considering this study was done with only case of boron content(5 wt%), further enhancement in Isp could be expected with higher boron content. Given that boron addition was done with only one case, the results are not conclusive. Future studies will carry out more combustion tests with higher boron contents to validate the results. In addition, staged combustion tests will be carried out to optimize the secondary combustor and to improve the combustion efficiency.

Acknowledgement

This work was supported by the National Research Foundation(NRF-2015R1D1A1A01058070) in the Republic of Korea.
References

[1] Lee, D., and Lee, C., “Hybrid Gas Generator for a Staged Hybrid Rocket Engine,” Journal of Propulsion and Power, 2016, accessed July 4, 2016. doi: http://arc.aiaa.org/doi/abs/10.2514/1.B36036

[2] George, P., Krishnan, S., Varkey, P. M., Ravindran, M., and Ramachandran, L., “Fuel Regression Rate in Hydroxyl-Terminated-Polybutadiene/Gaseous-Oxygen Hybrid Rocket Motors,” Journal of Propulsion and Power, Vol. 17, No. 1, 2001, pp. 35–42. doi:10.2514/2.5704

[3] Frederick, R. A., Jr., Whitehead, J. J., Knox, L. R., and Moser, M. D., “Regression Rates Study of Mixed Hybrid Propellants,” Journal of Propulsion and Power, Vol. 23, No. 1, 2007, pp. 175–180. doi:10.2514/2.704

[4] Einav, O., Peretz, A., Hashmonay, B., Birnholz, A., and Sobe, Z., “Development of a Lab Scale System for Hybrid Rocket Motor Testing,” 45th AIAA Joint Propulsion Conference, AIAA Paper 2009-4888, August 2010.

[5] Pilon, B., and Louwers, J., “Development of Staged Combustion Aft-Injected Hybrid (SCAIH) Propulsion at Cesaroni Technology Inc,” 46th AIAA Joint Propulsion Conference, AIAA Paper 2010-6786, July 2010.

[6] Karabeyoglu, A., Stevens, J., Geyzel, D., Cantwell, B., and Micheletti, D., “High Performance Hybrid Upper Stage Motor,” 47th AIAA Joint Propulsion Conference, AIAA 2011-6025, August 2011.

[7] Cantwell, B., Karabeyoglu, A., and Altman, D., “Recent Advances In Hybrid Propulsion,” International Journal of Energetic Materials and Chemical Propulsion, Vol. 9, No. 4, 2010, pp. 305-356. doi: 10.1615/IntJenergeticMaterialsChemProp.v9.i4.20

[8] Young, G., “Metallic Nano-Particles as Fuel Additives in Air-Breathing Combustion,” Ph.D. Dissertation, Aerospace Engineering Dept. Univ. of Maryland, College Park, MD, 2007.

[9] Evans, B., Boyer, E., Kuo, K. K., Risha, G., and Chiaverini, M., “Hybrid Rocket Investigations at Penn State University’s High Pressure Combustion Laboratory: Overview and Recent Results,” 45th AIAA Joint Propulsion Conference, AIAA 2009-5349, August 2009.

[10] Foelsche, R. O., Burton, R. L., and Krier, H., “Boron Particle Ignition and Combustion at 30-150 ATM,” Combustion and Flame, Vol. 117, No. 1-2, 1999, pp. 32-58. doi: 10.1016/S0010-2180(98)00080-7

[11] Risha, G. A., Evans, B. J., Boyer, E., Wehrman, R. B., and Kuo, K. K., “Nano-sized Aluminum- and Boron-based Solid-fuel Characterization in a Hybrid Rocket Engine,” 39th AIAA Joint Propulsion Conference, AIAA Paper 2003-4593, July 2003.

[12] Thomas, J. C., Petersen, E. L., DeSain, J. D., and Brady, B. B., “Enhancement of Regression Rates in Hybrid Rockets with HTPB Fuel Grains by Metallic Additives,” 51st AIAA Joint Propulsion Conference, AIAA Paper 2015-4041, July 2015.

[13] Shin, K. H., Won, J., Tak, H., Choi, S. H., Lee, W., and Lee, C., “A Static Combustion Study on Fuel Rich Propellant for Ducted Rocket Gas Generator,” 50th AIAA Joint Propulsion Conference, AIAA Paper 2014-4045, July 2014.

[14] Karabeyoglu, A., Toson, E., and Evans, B., “O/F Shift in Hybrid Rockets,” 50th AIAA Joint Propulsion Conference, AIAA 2014-3851, July 2014.

[15] Humble, R. W., Henry, G. H., and Larson, W. J., Space Propulsion Analysis and Design, Space Technology Series, McGraw–Hill, New York, 1995, pp. 365–441.

[16] Zilliac, G., and Karabeyoglu, M. A., “Hybrid Rocket Fuel Regression Rate and Modeling,” 42nd AIAA Joint Propulsion Conference, AIAA Paper 2006-4504, July 2006.