Solid Fuel Grain Design of 90% Hydrogen Peroxide/Polyethylene Solid Fuel Hybrid Rocket Engine

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The 90% hydrogen peroxide (HP), concentrated in lab-scale from Japanese domestic production of commercial grade HP, currently regulated below 60% for storing and handling safety have been applied to single and multi perforation polyethylene (PE) experimental hybrid rocket solid fuel. Modified 3-way catalysts have been utilized for decomposing the HP. Though the temperature of the decomposed products of HP attain higher than auto-ignition with almost fuels, a liquid rocket engine utilized for assisting solid fuel ignition and decreasing combustion pressure built-up time. In order to find oxidizer mass flux for sustaining hybrid rocket combustion, large fuel length/burning port diameter ratio (L/D=35) transparent polymethylmetacrylate (PMMA) solid fuel small hybrid rocket studies also have been carried out. The oxidizer mass flux has to be over the flux that extend diffusion flame up to the aft end of the solid fuel. The required minimum oxidizer mass flux was confirmed for the multi perforation solid fuel grain. Comparing solid propellant rocket grain, multi spoke wagon wheel and multi hexagonal perforation solid fuel grain designs were discussed.

Nomenclatures

\[ a = \text{solid fuel burning surface regression rate constant in } r_{s} = a \ G_{ox}^{n} \ [\text{m/s}]/[\text{kg/m}^{2}\cdot\text{s}]^{n} \]
\[ A_{b} = \text{solid fuel burning port surface area} \ [\text{m}^{2}] \]
\[ A_{c} = \text{solid fuel burning port cross sectional area} \ [\text{m}^{2}] \]
\[ D_{p} = \text{solid fuel burning port diameter} \ [\text{m}] \]
\[ G_{ox} = \text{oxidizer mass flux} \ [\text{kg/m}^{2}\cdot\text{s}] \]
\[ I_{sp} = \text{specific impulse} \ [\text{N-s/kg}] \text{ or } [\text{s}] \]
\[ k = \text{core and tail flame length ratio } (L_{DFC}/L_{DFC}) \]
\[ L_{DFC} = \text{core diffusion flame length formed on solid fuel burning surface} \ [\text{m}] \]
\[ L_{DFT} = \text{successive flame tail length after the core on solid fuel burning surface} \ [\text{m}] \]
\[ L_{DFP} = \text{total diffusion flame length } (=L_{DFC} + L_{DFT}) \text{ formed on solid fuel burning surface} \ [\text{m}] \]
\[ L_{SF} = \text{solid fuel length} \ [\text{m}] \]
\[ m_{f} = \text{fuel mass flow rate} \ [\text{kg/s}] \]
\[ m_{ox} = \text{oxidizer mass flow rate} \ [\text{kg/s}] \]

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The research and development works of hybrid rocket, which have been suspended these 30 years have been revived using mainly LOX or GOX and HP as oxidizer with HTPB or PE solid fuel for improving environmental impact due to the harmful solid booster rocket exhausts. As liquid rocket oxidizer, comparing with 100% oxygen LOX, obtainable Isp are about 10% less than LOX as 90% HP contains only 29% oxygen though, the obtainable Isp, about 274s @10 [MPa] combustion pressure are much higher than current high performance solid propellant rocket. The main advantages of HP are that: (a) storability, not cryogenic is easy to handling, (b) about 22% higher density than LOX result in higher tank volumetric efficiency, (c) the higher optimum O/F ratio 7.2 and lower combustion temperature both than LOX are easy to increase high combustion pressure in conjunction with small combustion chamber which result in higher Isp, (d) with PE solid fuel hybrid rocket, combustion and exhaust products are not only extra low environmental impact but also main low molecular mass H2O combustion product brings relatively high Isp even at low combustion temperature as Isp ~ (Tc/M)^{1/2}.

In Japan, once produced the 80-90% HP and had been applied to rocket engine of “Shusui” interceptor or advanced torpedo engine at the end of World War II. After the War, the revival production of 90% rocket grade (R/G) HP was utilized for reaction control system rocket in early 1960th. But the R/G 90% HP productions have been discontinued except commercial grade (C/G) HP because of serious accident happened in concentrator. Now, the Japanese domestic productions of extra high purity and stable C/G HP for chemical industries are more than 300,000 tons/year (reduced 100%), its concentration still currently regulated below 60% for handing, storages and shipping safety, (The industries are planning to increase the concentration up to 70% in near future for saving about 15% shipping cost.) The domestic C/G HP have been concentrated with 1 liter lab scale rotary evaporator to 90% for present 90% HP/PE hybrid rocket studies. Usually, the HP is decomposed passing through catalyst bed in advance to introduce into the solid fueled hybrid rocket combustion chamber. As the catalyst, piled up 70 to 130 silver net stack are widely utilized though, modified 3Pt/7Pd loaded 3-way catalyst have been utilized for decomposition catalyst in the present experimental studies.

II. Experimental Engine and Solid Fuel Design
In order to design experimental hybrid rocket engine, modeling currently utilizing solid rocket boosters SRB-A for H-IIA and M-14 for M-V launch vehicle a hybrid rocket booster HBR-X, Fig. 1. and solid fuel grain, Fig. 2. were temporarily designed. The HRB-X hybrid rocket booster and modeled booster rockets comparison are Table 2. The multi perforation type solid fuel grain for the HRB-X also designed under the consideration of very low average burning surface regression rate compared to solid propellant about 0.33 [mm/s]. The fuel element is O.D.130/I.D.90, and 3,150 long; (L/D=35) PE cylinder.

In order to study the combustion characteristics of hybrid rocket, three type experimental engines are provided for firing tests (Fig. 3). The head block consisted of HP injector assembly, decomposition chamber and pre-combustion chamber is common to the engines.

The type I engine (Fig. 3. A) is for testing 1/7.5 scale model PMMA solid fuel element and aft combustion chamber for observing the combustion behavior of fuel element. The transparent solid fuel served both as fuel and motor case utilize the direct observation of burning surface. The type II engine (Fig. 3. B) is for testing 1/3 scale model solid fuel element. The type III engine (Fig. 3. C) is for testing 1/10 scale model 7 perforations solid fuel. The experimental solid fuel provided for the tests were tabulated below.

<p>| Table 3. Experimental Solid Fuels |</p>
<table>
<thead>
<tr>
<th>Scale</th>
<th>Perforation</th>
<th>L/D=35</th>
<th>30</th>
<th>20</th>
<th>Length [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/3</td>
<td>30φ×1</td>
<td>1,050</td>
<td>900</td>
<td>600</td>
<td></td>
</tr>
<tr>
<td>1/7.5</td>
<td>12φ×1</td>
<td>420</td>
<td>----</td>
<td>----</td>
<td></td>
</tr>
<tr>
<td>1/10</td>
<td>9φ×7</td>
<td>----</td>
<td>270</td>
<td>180</td>
<td></td>
</tr>
</tbody>
</table>

The 3-way catalyst, designed for motor-bike was charged in the decomposition chamber. Original catalyst cartridge; 38φ×150ℓ employed for C/G grade HP though, it was too much active and often dangerous for 90% HP. Therefore, decomposition test was conducted with about a half long cut of original cartridge (60/90ℓ) or the combination of 10ℓ and 25ℓ cut of the catalyst cartridge. The HP decomposition took place quickly and smoothly without liquid phase H2O at the test of below the HP flow rate 0.2 [kg/s]. However, the temperature of decomposed products did not attain to calculated 750 °C. due to the incomplete decomposition and also auto ignition of solid fuel did not take place. After all, solid fuel ignition was made with assistance of about 1 second duration liquid rocket igniter torch. As long as utilize the igniter torch for igniting the solid fuel, the HP is not necessarily complete decomposition, a 19ℓ cut catalyst has been utilized.
III Assumption of Combustion Model in the Hybrid Rocket and Firing Test Results.

The typical solid fuel combustion in hybrid rocket is the diffusion flame that ignited at forward top end of solid fuel in the boundary layer near on the solid fuel burning surface. The diffusion flame consisted of the core flame which last to the point where the oxygen in the oxidizer consumed and accompanies successive high temperature burnt gases tail flame as shown in Fig. 4. Under the diffusion flame, usually gasified fuels are fed into the flame zone from the burning surface of solid fuel grain perforation. From the solid fuel surface after the diffusion flame no fuel or only slight fuel are fed into and they are formed sooty smoke succeeded by tail flame. Since the fuel generated from the burning surface by heat transfer from the flame, the diffusion flame have to be last up to the aft end of solid fuel or \( L_{DF} \geq L_{SF} \).

Although the local solid fuel burning surface regression rate along solid fuel is increased at right after down stream of forward end as seen in Fig. 4, due to the high heat transfer rate caused by steep temperature gradient formed by thin boundary layer, the average regression rate under the diffusion flame is expressed as

\[
rb = a \cdot G_{ox}^n
\]

Where \( a, n \) are estimated \( a=7.5\pm2.5\cdot10^{-6} \) for PMMA, \( a=12.5\pm2.5\cdot10^{-6} \) for PE, and \( n=0.65-0.7 \) (calculated as \( 2/3 \)) for both solid fuel, respectively. Fuel and oxidizer mass flow rate and their mixture ratio; O/F under the core diffusion flame are;

\[
m_f = \pi \cdot D_p \cdot L_{DFC} \cdot \rho_f \cdot rb = \pi \cdot D_p \cdot L_{DFC} \cdot \rho_f \cdot a \cdot G_{ox}^n
\]

\[
m_{ox} = \left( \frac{\pi}{4} \right) \cdot D_p^2 \cdot G_{ox}
\]

then the mixture ratio expressed as

\[
O/F = m_{ox}/m_f = \left[ 1/(4 \cdot a \cdot \rho_f \cdot (L_{DFC}/D_p)) \right] G_{ox}^{1-n}
\]

Since the core diffusion flame burning from the solid fuel top just under the boundary layer is sustained nearly stoichiometric; (O/F)\(st\) combustion, the dimensionless core flame length becomes

\[
L_{DFC}/D_p \cdot \left[ 1/(4 \cdot a \cdot \rho_f \cdot (O/F)_{st}) \right] G_{ox}^{1-n}
\]

In the hybrid rocket combustion chamber, the solid fuel burning surfaces have to be covered with the diffusion flame for ridding residual fuel as no fuel generation without diffusion flame.

Putting the relation between \( L_{DFC} \) and \( L_{SF} \) is expressed as; \( L_{DFC}/L_{DF} = k \).

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**Fig. 4. Assumed solid fuel combustion model in the hybrid rocket.**

**Fig. 5. Typical solid fuel combustion.**

**Fig. 6. Fuel regression rate \( rb \) vs \( G_{ox} \)**
\[ L_{DF} = (L_{DFc} + L_{DFt}) = (1+k) \cdot L_{DFc} \geq L_{SF} \]  \hspace{1cm} \text{-----------------------(6)}

and the oxidizer mass flux necessary for hybrid rocket becomes;

\[ G_{oa} \geq \left[ \frac{4 \cdot \alpha \cdot \rho_f \cdot (O/F)_{st} \cdot (L_{SF}/D_p)}{(1+k) \cdot \frac{1}{(1-n)}} \right] \hspace{1cm} \text{-----------------------(7)}

The core and tail flame ratio \( k \) is estimated from the flame luminosities of Fig. 5., obtained ID 12/OD 20×420\( \ell \); \( L_{SF}/D_p = 35 \) PMMA solid fuel experimental engine firing test, as \( 0.5 \leq k \leq 0.75 \). Substituting estimated \( n=2/3 \), necessary oxidizer mass flux \( G_{oa} \) for the HP/PE hybrid rocket are rapidly increasing proportional \( L_{SF}/D_p \) to the power 3rd as shown in Fig. 7.

In Fig. 7, the hybrid rocket combustion on the line \( k=0 \) is optimum condition that just the core flame cover the whole burning surface of the solid fuel. Therefore the exhaust plum is almost transparent and both the maximum thrust and \( \text{Isp} \) are obtainable. Fig. 8 shows the exhaust plum nearly on the line \( k=0 \) combustion. The combustion products formed in the region I, left side of the line \( k=0 \) is oxygen rich and exhaust also becomes completely transparent.

Usually the hybrid rocket is operated in the region II, between the line \( k=0 \) and \( k=0.75 \). The combustion products formed within the region are fuel rich, and then the exhaust plum forms large secondary diffusion flame mixing with ambient air. The throttling, a strong point of the hybrid rocket, is performable also within the region. According to the Fig. 7., the throttling is possible from 100 to 25\% (estimated \( k=0.75 \)) without residual solid fuel, though, the throttling is preferable to stop up to 50\% for stabilizing combustion.

The combustion in the region III, the right side of the line \( k=0.75 \), the diffusion flame formed on the solid fuel burning surface dose not reach to the aft end of the solid fuel. Therefore the combustion is quenched ahead of the nozzle inlet and the large amount of sooty smoke are exhausted as shown in Fig. 9. Fig. 10. shows the residual fuel of previous firing test with original fuel and motor case. As seen in the Fig. 10. although the forward part of the fuel were almost completely burnt, the aft part fuel did not due to the shortage of oxidizer flow and remained as residual fuel.

The introduction of the tail flame, the high temperature burnt gas trailing of core flame into the combustion model of hybrid rocket lead to better understanding of the firing test results with the relation between oxidizer mass flux and solid fuel length; Fig. 7.
IV Solid Fuel Grain Design

In so far, the hybrid rocket experiments had been carried out with simple single or multi circular perforation solid fuels though, new grain design for considering large thrust booster rocket have to be developed. In the both solid rocket propellant and hybrid rocket solid fuel grain, all burning surfaces regress in a direction normal to the surfaces of the grain until the web. However, different from the solid propellant, the regression rate of hybrid rocket solid fuel are far below the solid rocket propellant burning rate; nearly 1/10, so the solid fuel have to be large burning surface area and thin web thickness comparing solid propellant. One another difference between solid propellant and solid fuel is that the burning surface area change of solid propellant directly changes combustion pressure and thrust, for instance circular perforation perform progressive burning but in the case of solid fuel, the pressure and thrust are sustained almost natural, since the surface area expansion, the cross sectional area expansion led to the oxidizer mass flux and regression rate decrease at the same time.

Therefore, the hybrid rocket solid fuel grains have to be designed for increasing burning surface area (BSA), decreasing sliver, useless as fuel, for increasing effective area loading factor (EALF), without consideration of the BSA change in the course of combustion. The modifications of basic 7-circular perforations experimental solid fuel grain design to decrease sliver are shown in Fig. 11.

As seen in Fig. 11., the slivers of basic 7-circular perforations experimental solid fuel grain design are slightly decreased by simple deformation of circular to hexagonal perforation, remarkably decrease by wagon wheel grain. These modifications increase not only EALF but also BSA keeping initial web thickness at the present experimental $\phi 50$ fuel as written under the each grain design. Among them, 7-spokes wagon wheel/hub grain (right end) was considered the most harmonized grain. Therefore, the firing test was conducted; (Fig. 12.). The solid fuel forward end surface before and after the test and residual fuel were shown in Fig. 13. The secondary diffusion flame is seen in exhaust plum and the fuel consumption seems to be normal due to the firing test was conducted at within the region II of Fig. 7.

![FIG. 11. SIMPLE MODIFICATION OF SLIVER DECREASING OF SOLID FUEL GRAIN.](image)

![FIG. 12. FIRING TEST OF L/S/Dp = 20, Gox = 130[kg/m²-s] WAGON WHEEL FUEL WITH P-T CURVE.](image)

![FIG. 13. WAGON WHEEL SOLID FUEL](image)
As the solid fuel grain for $\phi 2,500$ temporarily designed engine; Fig. 1 and 2, simply enlarged 7-spoke wagon wheel with hub grain design is holding small silver, though, the burning surface area is too small and web is too thick, that require high regression fuel for satisfying thrust and burning time requirement. These defects are improvable some extent by spoke increasing, though, about twice high regression rate is necessary even for 24-spoke wagon wheel design. Therefore, as long as high regression rate fuel undeveloped, hexagonal multi perforation grain design comes in useful. The solid fuel and combustion chamber length are shorten by the conversion circular to hexagonal perforation as the burning surface is increased about 10%.

**V Conclusions**

Utilizing 90% HP, concentrated domestic 60% commercial grade in lab scale as an oxidizer, polyethylene solid fuel hybrid rocket have been evaluated.

The decomposition chamber and catalyst are key component for the HP rocket. Appropriately cut of 3-way catalyst cartridge, designed for cleaning motor-bike engine exhaust have been applied for the present work, The decomposition were performed safely and much actively than usual silver net catalyst stack.

In order to normally perform hybrid rocket solid fuel combustion, the length of diffusion flame formed on the solid fuel burning surface has to be nearly equal or longer than solid fuel length. For satisfying the requirement, oxidizer mass flux has to be $G_{\text{ox}} \geq \frac{(4 \cdot a \cdot \rho_f \cdot (O/F)_{st} \cdot (LS/V)_{fr} \cdot (1+k))}{(1+n)}$.

The thrust of the hybrid rocket is throttleable by the oxidizer throttling, though, the diffusion flame length has to be longer than solid fuel, because of the over throttling cause after solid fuel combustion to run short.

Wagon wheel grain design is suitable for small engine though, application for large engine have to involve the development of high regression rate fuel.

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**References**