Article

Estimation of highest burning rate of AP/HTPB composite propellant with experimental approach (II)
– Estimation of highest burning rate by use of AP particle property –

Makoto Kohga* and Yutaka Hagihara*

The upper limit content of AP incorporated in AP/HTPB composite propellant, ϕ_{max} exists because of the requirements for the preparation of propellant. The burning rate increases with increasing the AP content and the burning rate of the propellant prepared at ϕ_{max}, r_ϕ is the highest value of the propellant prepared with AP used as an oxidizer. It is necessary to estimate r_ϕ because the burning rate is one of the important properties for the propellant design. An attempt was made to find out the estimation of r_ϕ with the experimental approach in this study.

As the specific surface area, S_W increases, r_ϕ increases below 700 $m^2 \cdot kg^{-1}$ and decreases above that. This relationship is expressed by a convex line. It is found that the r_ϕ can be estimated by S_W on the basis of the plot of r_ϕ versus S_W. The upper limit of r_ϕ exists and r_ϕ of propellant prepared with AP, of which S_W is 700 $m^2 \cdot kg^{-1}$, is the maximum value of AP/HTPB composite propellant. The maximum of r_ϕ is 25.2 $mm \cdot s^{-1}$ at 7 MPa in this study. It is found that r_ϕ is dependent on ϕ_{max} and S_W greatly, and the maximum value of r_ϕ could be obtained at the particular combination of ϕ_{max} and S_W. The effect of ϕ_{max} on r_ϕ was corrected by the multiplication of ϕ_{max} by the increasing ratio of the burning rate upon S_W. The effect of S_W on r_ϕ was corrected by the multiplication of S_W by the increasing ratio of the burning rate upon the AP content.

1. Introduction

For the design of a composite propellant, the burning rate is one of the important properties. As the burning rate increases, the amount of combustion gas per unit time increases and larger thrust could be obtained. Therefore, a higher burning rate propellant is required. The burning rate of ammonium perchlorate (AP)/hydroxyl - terminated polybutadiene (HTPB) composite propellant increases with increasing AP content. The larger AP content of the propellant should be required to obtain the higher burning rate AP/HTPB composite propellant. The upper limit content of AP incorporated in propellant, ϕ_{max} exists because of the requirements for the preparation of AP/HTPB composite propellant[1,2]. The burning rate of the propellant prepared at ϕ_{max}, r_ϕ is the highest value of the propellants prepared with AP used as an oxidizer. It is important for the design of AP/HTPB composite propellant to estimate r_ϕ. The burning rate characteristics of AP/HTPB composite propellant have been investigating, however, r_ϕ have little been published to date.

In the previous study[3], a lot of propellants were prepared with many kinds of AP samples, e.g. spherical AP, porous AP, hollow AP, narrow distribution, wide distribution, monomodal, bimodal, etc., and the burning rate characteristics of the propellants were investigated in order to develop the estimation of r_ϕ with the experimental approach. The following results were obtained: 1) The ranges of ϕ_{max} and r_ϕ at 7 MPa are 72 – 85 wt% AP and 11.7 – 25.2 $mm \cdot s^{-1}$, respectively. 2) The increment of burning rate increased remarkably with coming close to ϕ_{max}. The increasing ratio of the burning rate upon the AP content, α increases with increasing specific surface area less than 500 $m^2 \cdot kg^{-1}$, and is the maximum and almost constant above that. 3) The increasing ratio of the burning rate upon the

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*Department of Applied Chemistry, National Defense Academy, 1-10-20, Hashirimizu, Yokosuka-shi, Kanagawa, 239-8989, JAPAN
TEL +81-46-841-3810 (ext. 3585)
FAX +81-46-844-5901
E-Mail kohga@nda.ac.jp

specific surface area, β increases linearly with the AP content. In this study, an attempt was made to find out the estimation of r_ϕ on the basis of the previous paper[3].

2. Experimental

The particle properties of AP samples are shown in Table 1. These samples were the same as materials used in the previous report[3]. Samples A−E were prepared by grinding commercial AP for 5, 10, 20, 30 and 40 minutes in a vibration ball mill. The shape of samples A−E was spherical and the particle size distribution was wide. Sample F was prepared by shifting sample E. Sonic sifter was used as a sifter. Sample F was AP particles passed 38 μm. The shape of sample F was spherical and this particle size distribution was narrow. Samples G − Q were prepared by the spray-drying method[4-6]. Samples R and S were prepared by the freeze-drying method[7]. The shapes of samples G−I, samples J−O and samples P−S were spherical, porous and hollow, respectively. Samples a − h were the mixture of two AP samples and, therefore, these distributions were bimodal. The mean volume-surface diameter on number basis, D_{vs} and the specific surface area, S_W are shown in Table 1. The D_{vs} was measured by use of the SEM photographs and S_W was determined by air-permeability method. The ranges of D_{vs} and S_W are 2−110 μm and 40−1200 $m^2 \cdot kg^{-1}$, respectively.

The burning rate characteristics were also investigated in the previous report. Table 1 also shows ϕ_{max}, r_ϕ, and α. Table 2 shows the value of β at each AP content.

Table 1 Particle properties of AP and burning rate characteristics of propellant

Symbol	D_{vs} (μm)	S_W ($m^2 \cdot kg^{-1}$)	ϕ_{max} (wt%)	r_ϕ ($mm \cdot s^{-1}$)		α (-)	β_ϕ (-)
				1 MPa	7 MPa		
A	110	40	85	5.3	11.7	1.7	0.0400
B	70	50	85	5.3	12.1	1.9	0.0400
C	50	100	84	5.4	12.4	2.1	0.0376
D	40	150	83	5.4	12.8	2.6	0.0364
E	40	180	83	5.5	14.2	3.1	0.0364
F	20	260	82	5.7	15.1	3.5	0.0334
G	2	1010	75	6.2	16.9	4.6	0.0113
H	2	940	76	6.9	19.8	4.7	0.0163
I	3	900	77	7.2	21.8	4.3	0.0182
J	6	1060	73	5.8	15.4	5.2	0.0061
K	8	450	80	6.9	19.1	4.5	0.0298
L	7	780	77	7.4	24.2	5.5	0.0182
M	4	840	77	7.1	23.1	4.5	0.0182
N	3	990	74	6.2	17.2	5.1	0.0094
O	4	860	76	7.1	21.1	4.8	0.0163
P	3	1200	72	4.7	13.1	5.0	0.0046
Q	3	1160	72	5.2	12.2	4.7	0.0046
R	4	610	80	9.3	24.6	4.9	0.0274
S	11	370	81	7.5	19.5	5.2	0.0298
a	2	480	80	7.2	20.5	4.7	0.0274
b	10	470	80	7.3	19.8	4.9	0.0274
c	5	550	80	8.9	22.8	4.5	0.0274
d	9	220	83	5.9	13.5	3.0	0.0364
e	6	310	82	6.2	14.2	3.5	0.0334
f	2	820	78	7.2	22.2	5.2	0.0215
g	2	690	79	8.9	25.2	5.1	0.0240
h	2	630	79	9.1	25.1	5.4	0.0240

Table 2 Value of β at each AP content

AP content (wt%)	β (-)
72	0.0046
73	0.0061
74	0.0094
75	0.0113
76	0.0163
77	0.0182
78	0.0215
79	0.0240
80	0.0274
81	0.0298
82	0.0334
83	0.0364
84	0.0376
85	0.0400

3. Results and discussion

3. 1 Estimation of r_ϕ

The burning rate is affected by the AP content. This suggests that r_ϕ would be related to ϕ_{max}. Figure 1 shows the dependence of ϕ_{max} on r_ϕ. As ϕ_{max} increases, r_ϕ increases less than 79.5 wt% AP and decreases above that. The r_ϕ is greatly influenced by the AP content, however, the values of r_ϕ are different at constant ϕ_{max}. For example, the values of ϕ_{max} for propellants K, R, b and c are constant, 80 wt% AP, and r_ϕ of these propellants is different from one another according to Table 1. The difference in r_ϕ between propellants K and R is 5.5 mm·s^{-1} at 7 MPa and this value cannot be neglected with regard to estimation of r_ϕ. These results indicate that r_ϕ is influenced by ϕ_{max}, however, r_ϕ cannot be estimated by ϕ_{max} only.

The burning rate increases with decreasing diameter of AP or increasing specific surface area. The flame of AP composite propellant is a so called diffusion flame, and the model of Multiple Flames[8] is generally accepted as a model of the flame structure. According to the model of Multiple Flames, the oxidizer and binder decomposition products diffuse and mix and, consequently, the combustion occurs. It can be considered that the combustion of AP occurred on the surface of AP particle. Some porous and hollow AP samples were used in this study. This suggested that S_W would be an appropriate property to express the surface area of AP particle contributes to the combustion, compared with D_{v}. The S_W was used as the particle property to represent the size of AP particle relates to combustion in the following discussion.

The ϕ_{max} of propellant A is the largest in this study, however, r_ϕ of this propellant is the lowest. This would be because S_W of sample A is small. It can be considered that r_ϕ would be greatly dependent on ϕ_{max} and S_W and the highest value of r_ϕ could be obtained at the particular combination of ϕ_{max} and S_W. The ϕ_{max} can be estimated with S_W[2]. These suggests that r_ϕ can be expressed by S_W. Figure 2 shows the dependence of S_W on r_ϕ. As S_W increases, r_ϕ increases below 700 m^2·kg^{-1} and decreases above that. The relationship is expressed by a convex line. It is found that r_ϕ can be estimated

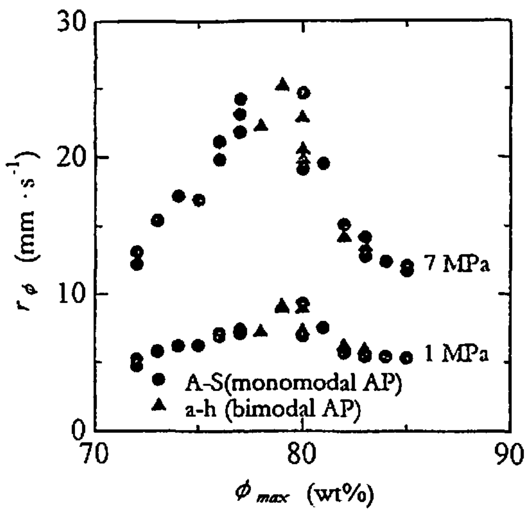

Fig.1 Dependence of ϕ_{max} on r_ϕ

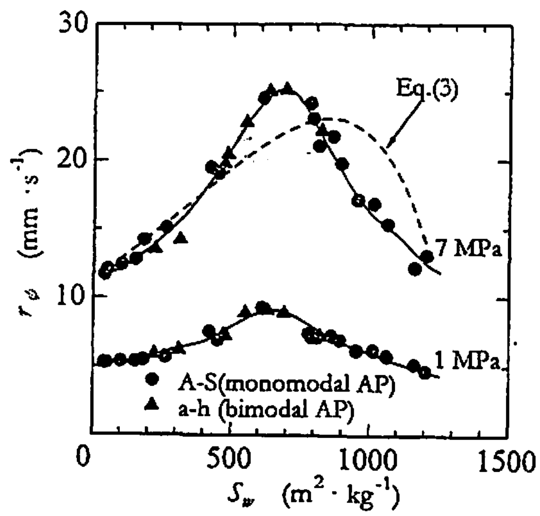

Fig.2 Dependence of S_W on r_ϕ

estimated by S_W on the basis of Fig.2.

The plot of log (burning rate) against log (pressure) for the propellant prepared at ϕ_{max} is approximately linear[3]. The r_ϕ at certain pressure could be estimated almost exactly by the straight line drawing with two points, the values of r_ϕ at 1 MPa and 7 MPa, on a log (burning rate) – log (pressure) graph. The r_ϕ at 1 MPa and 7 MPa can be estimated by S_W on the basis of Fig.2.

If the preparation of the propellant was different from that in this study, the value of r_ϕ would be varied. However, it was expected that r_ϕ could be estimated by S_W.

3. 2 Quantitative analysis

The relationship between r_ϕ and S_W is represented by a convex line as shown in Fig.2. This suggested that r_ϕ would be affected by two factors that one factor would cause to increase r_ϕ and another factor would cause to decrease r_ϕ as S_W increases. The influences of these two factors on r_ϕ were analyzed quantitatively below on the basis of the burning rate characteristics.

As mentioned in the previous section, r_ϕ would be influenced by ϕ_{max} and S_W greatly. The α represents the increasing ratio of the burning rate upon the AP content at the constant S_W. As S_W increases, α increases less than 500 $m^2 \cdot kg^{-1}$ and is approximately constant and the maximum above that[3]. It could be considered that the influence of S_W on r_ϕ could be expressed by the product of α and S_W. The αS_W was calculated on the basis of the data as shown in Table 1. Figure 3 shows the influence of S_W on αS_W. The αS_W increases with increasing S_W. It seems that the relationship is linear. However, the relationship is represented by a parabola line less than approximately 500 $m^2 \cdot kg^{-1}$, the broken line, in the case of the magnified scale because α increases with increasing S_W less than 500 $m^2 \cdot kg^{-1}$ [3].

The β represents the increasing ratio of the burning rate upon S_W at the constant AP content. The β increases linearly with the AP content[3]. The β corresponding to ϕ_{max}, β_ϕ of each AP sample was determined on the basis of data as shown in Table 2. The results are also shown in Table 1. It could be considered that the influence of ϕ_{max} on r_ϕ could be expressed by the product of β_ϕ and ϕ_{max}. The $\beta_\phi \phi_{max}$ was calculated on the basis of the data as shown in Table 1. Figure 4 shows the influence of S_W on $\beta_\phi \phi_{max}$. The $\beta_\phi \phi_{max}$ decreases linearly with increasing S_W.

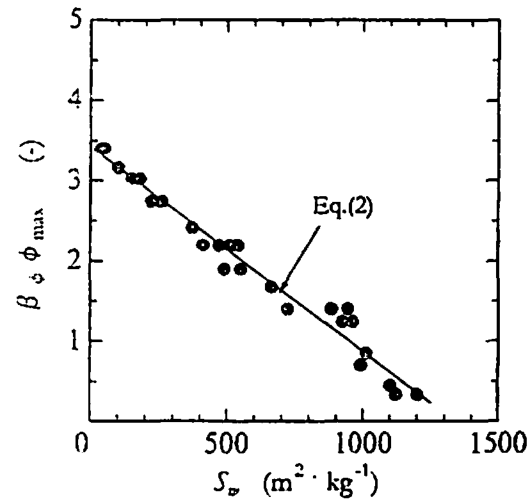

Fig.4 Influence of S_W on $\beta_\phi \phi_{max}$

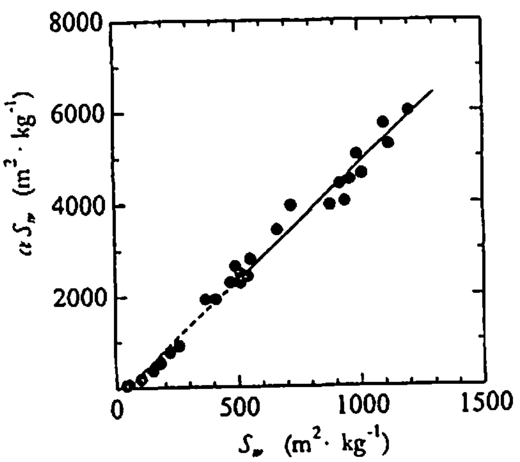

Fig.3 Influence of S_W on αS_W Relationship

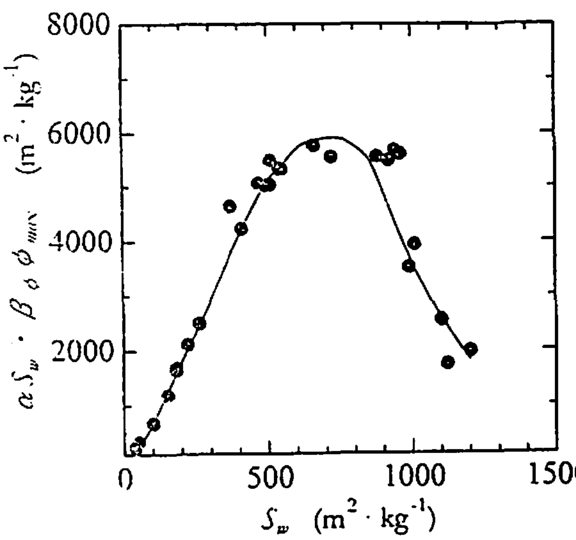

Fig.5 Relationship between $\alpha S_W \cdot \beta_\phi \phi_{max}$ and S_W

Figure 5 shows the relationship between $\alpha S_W \cdot \beta_\phi \phi_{max}$ and S_W. The relationship is expressed by a convex line. The $\alpha S_W \cdot \beta_\phi \phi_{max}$ increases below 700 $m^2 \cdot kg^{-1}$ and decreases above that, as S_W increases. This convex line is in a similar manner as the relationship between r_ϕ and S_W as shown in Fig.2. This fact suggests that r_ϕ is dependent on αS_W and $\beta_\phi \phi_{max}$ greatly.

The values of both αS_W and $\beta_\phi \phi_{max}$ should be larger in order to obtain higher r_ϕ. The larger αS_W is, the smaller $\beta_\phi \phi_{max}$ becomes as shown in Figs.3 and 4. This indicates that the upper limit of r_ϕ exists and r_ϕ of propellant prepared with AP, of which S_W is 700 $m^2 \cdot kg^{-1}$, is the maximum value according to Figs.2 and 5. The maximum burning rate of AP/HTPB composite propellant is 25.2 $mm \cdot s^{-1}$ at 7 MPa within the limits of this study.

An attempt was made to obtain the experimental equation to estimate r_ϕ at 7 MPa. The ratio of r_ϕ to $\beta_\phi \phi_{max}$, that is, $r_\phi/(\beta_\phi \phi_{max})$, was calculated on the basis of Table 1. Figure 6 shows the relationship between $r_\phi/(\beta_\phi \phi_{max})$ and S_W. The $r_\phi/(\beta_\phi \phi_{max})$ increases with increasing S_W. This relationship can be made the approximation with the following equation.

$$r_\phi/(\beta_\phi \phi_{max}) = 3.24 \exp(0.002 S_W) \quad (1)$$

As shown in Fig.4, $\beta_\phi \phi_{max}$ is closely associated with S_W. The relationship between $\beta_\phi \phi_{max}$ and S_W can be expressed by the following equation.

$$\beta_\phi \phi_{max} = 0.0026 S_W + 3.51 \quad (2)$$

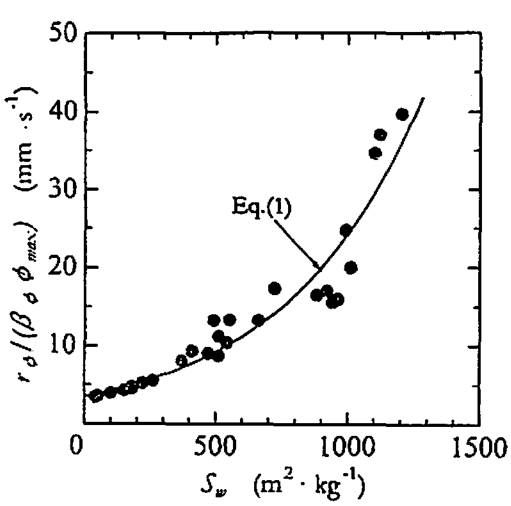

Fig.6 Relationship between $r_\phi/(\beta_\phi \phi_{max})$ and S_W

Substituting Eq.(2) into Eq.(1),

$$r_\phi = (0.0026 S_W + 3.51) \times 3.24 \exp(0.002 S_W) \quad (3)$$

Equation (3) is expressed by the broken line in Fig.2. Equation (3) is a convex line, however, this equation could not agree with the experimental values.

Some porous or hollow AP samples were used in this study. There is the bubble contamination in propellant prepared with porous or hollow AP which influence r_ϕ. In addition, r_ϕ would be not only affected by ϕ_{max} and S_W but also by the shape of AP, the distance between two adjacent AP particles in the propellant, the temperature gradient in the vicinity of the burning surface, the diffusion distance and gas reaction in the gas phase, etc. It is necessary to investigate the influences of these factors on the burning rate in order to obtain the accurate experimental equation for the estimation of r_ϕ. The experimental equation to estimate r_ϕ could not be obtained in this study, however, it is found that r_ϕ can be estimated by S_W on the basis of Fig.2.

4. Conclusions

The upper limit content of AP incorporated in AP/HTPB composite propellant exists, ϕ_{max} exists because of the requirements for the preparation of propellant. The burning rate increases with increasing the AP content and the burning rate of the propellant prepared at ϕ_{max}, r_ϕ is the highest value of the propellant prepared with AP used as an oxidizer. An attempt was made to find out the estimation of r_ϕ with the experimental approach in this study.

As the specific surface area, S_W increases, r_ϕ increases below 700 $m^2 \cdot kg^{-1}$ and decreases above that. This relationship is expressed by a convex line. It is found that the r_ϕ can be estimated by S_W on the basis of the plot of r_ϕ versus S_W. The upper limit of r_ϕ exists and r_ϕ of propellant prepared with AP, of which S_W is 700 $m^2 \cdot kg^{-1}$, is the maximum value of AP/HTPB composite propellant. The maximum of r_ϕ is 25.2 $mm \cdot s^{-1}$ at 7 MPa in this study. It is found that r_ϕ is dependent on ϕ_{max} and S_W greatly, and the maximum value of r_ϕ could be obtained at the particular combination of ϕ_{max} and S_W. The effect of ϕ_{max} on r_ϕ was corrected by the multiplication of ϕ_{max} by the increasing ratio of the burning rate upon S_W. The effect of S_W on r_ϕ was corrected by the multiplication of S_W by the increasing ratio of the burning rate upon the AP content.

The experimental equation to estimate r_ϕ could not be obtained because the influences of the other factors, except ϕ_{max} and S_W, on r_ϕ could not be revealed within the limits of this experiment. These influences should be investigated in detail for the future in order to obtain the accurate experimental equation to estimate r_ϕ.

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実験的手法によるAP/HTPB系コンポジット推進薬の最高燃焼速度の推算（II）
－APの粒子特性による最高燃焼速度の推算－

甲賀　誠*，萩原　豊*

AP/HTPB 系コンポジット推進薬には製造上の条件があるために，推進薬中に混入可能な AP 含有率の上限，ϕ_{max} がある。AP 含有率の増加にしたがい燃焼速度は増加し，ϕ_{max} で製造された推進薬の燃焼速度，r_ϕが，用いた AP で達成できる燃焼速度の最大値となる。AP/HTPB コンポジット推進薬を設計する上で，r_ϕを推測することは重要である。本実験では，実験的手法によって，r_ϕを推算する方法を見いだすことを試みた。

用いた AP の比表面積，S_Wが 700 $m^2 \cdot kg^{-1}$ 以下において，r_ϕはS_Wの増加にしたがい大きくなり，それ以上では減少した。r_ϕとS_Wの関係は凸曲線で表された。AP のS_Wを測定すれば，その AP のr_ϕはr_ϕとS_Wの関係をプロットした図から推測できることがわかった。r_ϕには上限があり，S_Wが 700 $m^2 \cdot kg^{-1}$ となる AP を用いて製造された推進薬のr_ϕが，AP/HTPB 系コンポジット推進薬が達成できる燃焼速度の最大値となることがわかった。本実験の範囲内では，r_ϕの最大値は 25.2 $mm \cdot s^{-1}$（7 MPa）であった。r_ϕはϕ_{max}とS_Wに大きく依存することがわかった。r_ϕに及ぼすϕ_{max}の影響は，S_Wに対する燃焼速度の増加率を乗ずることによって補正され，r_ϕに及ぼすS_Wの影響は，ϕ_{max}に対する燃焼速度の増加率を乗ずることによって補正されることがわかった。

（*防衛大学校　応用化学科　〒239-8989 横須賀市走水1－10－20）