Analytical Evaluation of the Solid Rocket Motor Nozzle Surface Recession by the Alumina-Carbon Reaction

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Abstract

A theoretical model describing the chemical ablation of a solid rocket motor nozzle ablator by the alumina-carbon reaction is presented. An application of it to a typical solid rocket motor with a graphite nozzle ablator indicates a large influence of the reaction on the nozzle surface recession.

1. Introduction

The nozzle inside of a Solid Rocket Motor (SRM) is exposed to the high enthalpy flow of the combustion gas, and hence the nozzle inside is composed of thermal protection materials, which are mainly carbonous ones. Improving the performance and reliability of the thermal protection materials for SRM nozzles is one of the issues in SRM technology, and has been addressed positively. At present, however, SRM failures are still frequently reported in the world. The number of demands for space applications using SRMs is expected to increase more and more in future years. Therefore, improving the performance and reliability of the thermal protection materials for SRM nozzles is still required.

Thermal protection materials ablate by the action of the flow of combustion gas, and consequently, the nozzle surface recesses. The recession influences on the elementary performances of a SRM and the thermal-structural performances of the nozzle since it changes the nozzle flow. Therefore, it is important in SRM technology to well evaluate the nozzle surface recession.

A variety of processes on the ablation of thermal protection materials have been proposed. Although thermal protection materials are applied not only to SRMs but also to atmospheric entry vehicles, one of the main differences between them is that SRM nozzle flow is a multiphase flow containing combustion products of condensed phase. The existence of this condensed phase in the flow complicates analyses on SRMs compared with those on atmospheric entry vehicles.

In order to evaluate the performance of thermal protection materials in high enthalpy flow, theoretical methods developed by NASA in the 1960s for atmospheric entry vehicles [1, 2] are in standard use involving applications on

SRMs. However, no standard method taking into account the influence of condensed phases in SRM nozzle flow has been developed: there are just a few particular models.

Two processes can be considered that the condensed phase directly contributes to the ablation of thermal protection materials: mechanical ablation by the collision of particles of the condensed phase, and chemical ablation by chemical reaction with the particles. As the authors know, there has been no study on the latter except Chiba's study [3]. In that study, experiments to collide alumina particles and carbon particles (as chemically inert particles) with plates of a thermal protection material were performed, and he asserted that the difference between those results is the contribution by chemical reaction.

The chemical reactivity between carbon and alumina has been discussed in metallurgy in view of technology on the carbothermal reduction of aluminum (e.g. [4]). And it could be noted that a model developed by Chiba is an empirical one which is not well discussed from chemical viewpoint.

This study presents a theoretical model describing the chemical ablation of a SRM nozzle ablator by the alumina-carbon reaction in terms of chemical viewpoint. And applying it to a typical SRM, an evaluation of the influence of this process on the SRM nozzle surface recession is performed.

2. Model

In this study, graphite is taken up as a nozzle ablator material, and hence an ablation model described here is for a non-charring material.

In neighborhood of the boundary between the combustion gas (including the condensed phase) and the nozzle ablator, gas phase, solid phase (graphite), and liquid phase (alumina) exist. It is assumed that the solid and liquid phases consist of single chemical species each, and that the gas phase consists of multiple chemical species. The balance of chemical element on the boundary is described as

$$Y_{(k)g}\dot{m}_g + J_{(k)g} - \alpha_{(k)s}\dot{m}_s + \alpha_{(k)l}\dot{m}_{(l)} = \alpha_{(k)l}\dot{m}'_{(l)}\,. \qquad (1)$$

Here, g, s, and l stand for gas, solid, and liquid phases, respectively. $\dot{m}$ is a mass flux relative to the speed of the nozzle surface recession. $\dot{m}_l$ is the mass flux of alumina impinging to the nozzle surface, and $\dot{m}'_l$ is the net accumulation rate of alumina on the boundary of unit area. $Y_{(k)g}$ is the mass fraction of chemical element k in the gas phase , and $\alpha_{(k)}$ is the mass fraction of chemical element k in one mole of each phase. $J_{(k)g}$ is the diffusional mass flux of chemical element k in the gas phase, and it is described by the mass transfer correlation

$$J_{(k)g} = g_m\left(Y^w_{(k)g} - Y^e_{(k)g}\right), \quad (2)$$

where g_m is a mass transfer coefficient, and w and e represent for wall and boundary layer edge, respectively. Applying Eq. (2) into (1) derives the relation on the boundary

$$Y^w_{(k)g} = \frac{Y^e_{(k)g} + \alpha_{(k)s}B_s + \alpha_{(k)l}B''_l}{1 + B_s + B''_l}. \quad (3)$$

Here,

$$B = \frac{\dot{m}}{g_m}, \quad B' = \frac{\dot{m}'}{g_m},$$

and

$$B''_l = B'_l + B^{in}_l, \quad B^{in}_l = -B_l.$$

B^{in}_l takes positive values for the impinging flux of alumina to the surface. B_s appearing in this equations is the ablation rate of the nozzle ablator. It is noted that setting B''_l to zero reduces this formulation to the case of no alumina impingement.

The chemical composition of the gas phase on the boundary is determined on an assumption that the gas phase is in chemical equilibrium with the solid phase (graphite) at the wall temperature and pressure. B'_l is set to zero, which means no net alumina accumulation on the nozzle wall.

3. Application

3.1 SRM Model

A typical SRM of a propellant composition of AP/HTPB/AL=65/15/20 and a throat radius of 0.3 m is considered. The combustion pressure is set to 10 MPa. The chemical composition of the combustion products in the combustion chamber is calculated using the CEA2 code [5], and the resultant adiabatic flame temperature is 3300 K. The nozzle station where the Mach number of the main stream of the nozzle flow is 2.0 is picked up here, and the ablation rate and the surface recession at this point is calculated. The nozzle main stream is calculated assuming to be a quasi one-dimensional, chemically equilibrium, and homogeneous flow. The resulting static pressure at this station is 1.5 MPa.

3.2 Ablation Rate

The calculated ablation rate with respect to the wall temperature is shown in Figure 1. The curve with B_l^{in} =0 is for the case of no-alumina impingement. This figure shows that the ablation rate increases with alumina impingement above about 1500 K.

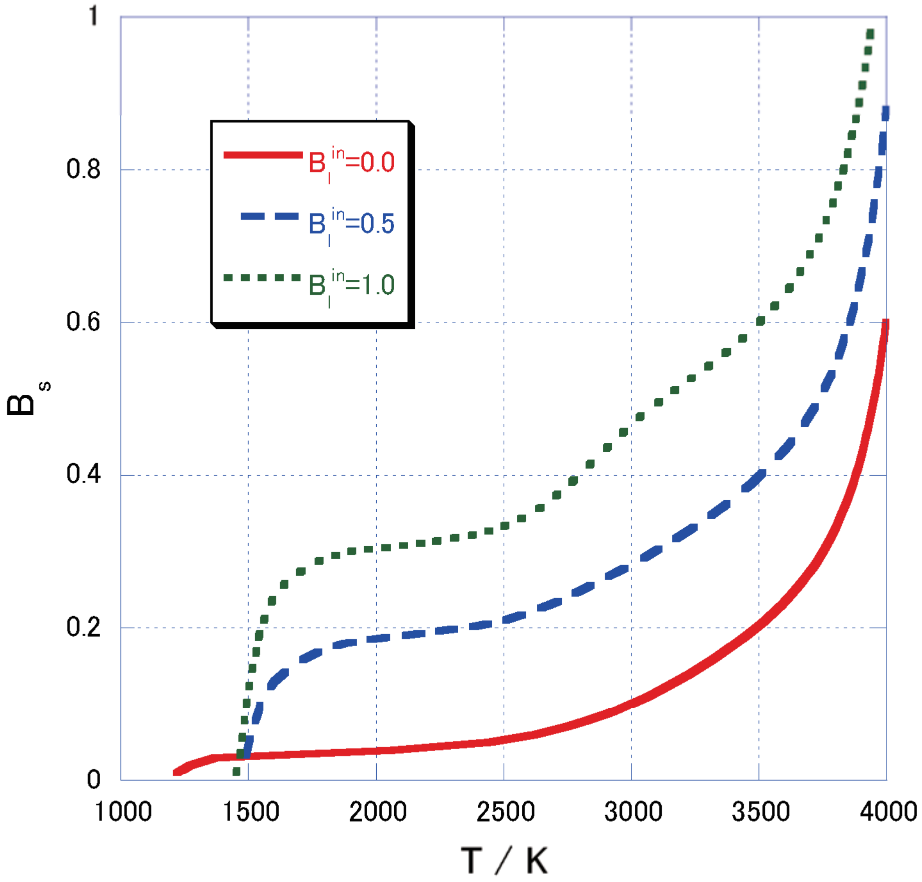

Figure 1 Ablation rate

3.3 Nozzle Surface Recession

The surface recession of the nozzle ablator is calculated by solving a heat conduction equation in the solid phase coupled with an energy balance equation on the surface using the above ablation rate. The wall temperature is determined in this calculation. The heat transfer coefficient in the energy balance equation is calculated by the Bartz formula [6].

Figure 2 shows the temporal history of the surface recession. The recession rate increases with alumina impingement. This increase in the surface recession rate with alumina impingement is attributed to the increase in the ablation rate with that shown in Fig. 1 because, from the temporal history of the wall temperature, the wall temperature exceeds 1500 K already after 5 s for each case.

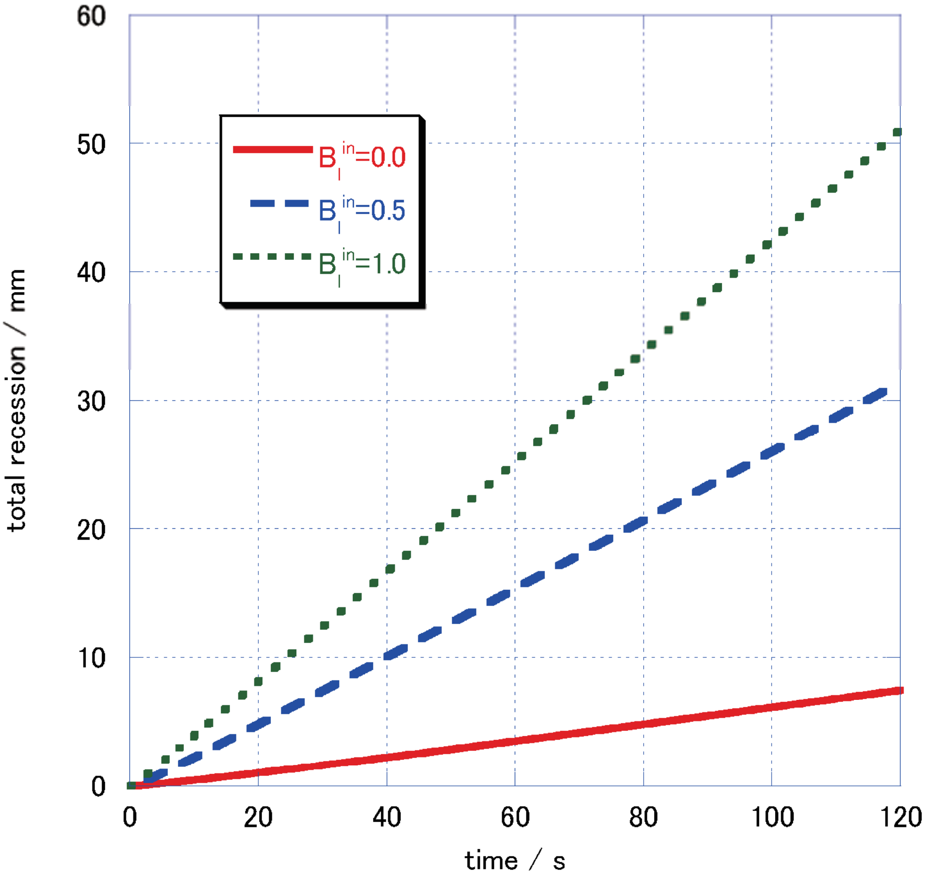

Figure 2 Surface recession

Figure 3 shows the ratio of the surface recession rate to that without alumina impingement (the rate with B_l^{in}=0). The ratio increases almost linearly with B_l^{in}. For the case of the SRM condition considered here, $B_l^{in}=1$ corresponds to an alumina impingement rate of about 3 kg/m^2·s, and it can be seen from this figure that the recession rate increases by a factor of about seven at this impingement rate. Although this study is not concerned with evaluating how much alumina impinges into the surface, it seems that this value of 3 kg/m²-s is not so large since the total mass flux at the nozzle throat is about 3000 kg/m²-s. These results show that the model presented in this study indicates a large influence of the alumina-carbon reaction on the nozzle surface recession.

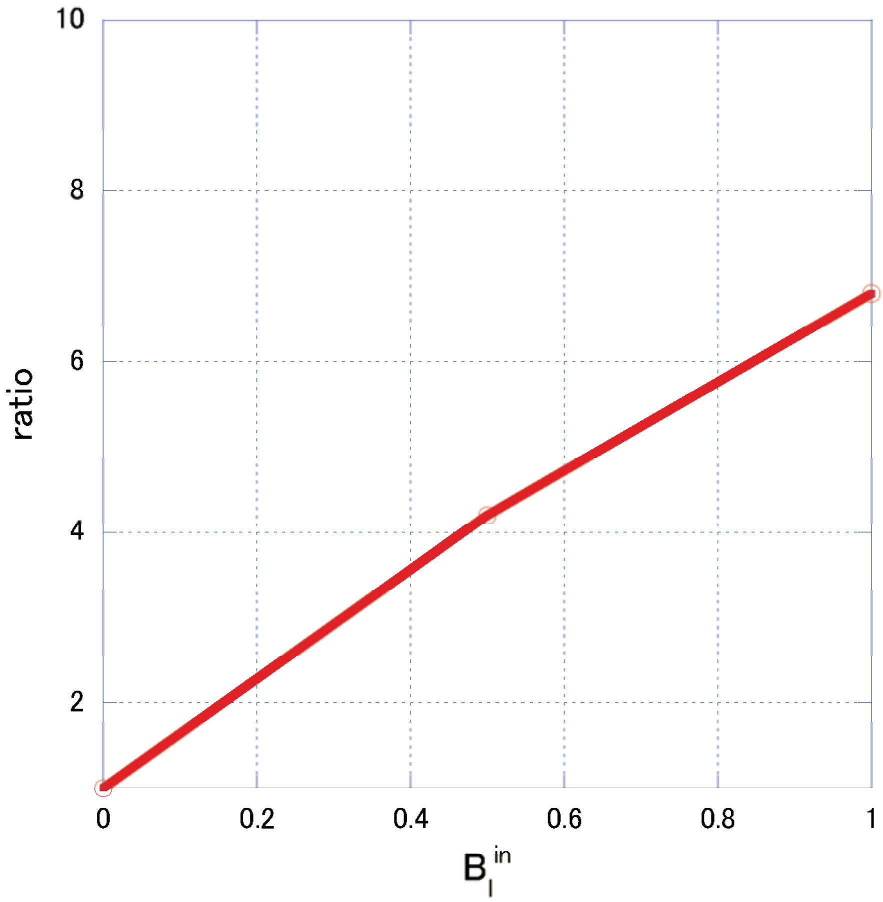

Figure 3 Ratio of the recession rate

4. Conclusion

A theoretical model describing the chemical ablation of a SRM nozzle ablator by the alumina-carbon reaction was presented. An application of it to a typical SRM with a graphite nozzle ablator indicated a large influence of the reaction on the nozzle surface recession.

References

1. Kendall *et al.*, AIAA J, 5(1967)1063.
2. Kendall *et al.*, NASA CR-1060 (1968).

3. Chiba, 1981 JANNAF Propulsion Meeting (1981)175.
4. Welch, JOM 51(1999)24.
5. Gordon and Mcbride, NASA RP-1311 (1994).
6. Bartz, Jet Propulsion 27(1957)49.