Recession Behavior of Graphitic Nozzles in Simulated Rocket Motors

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Abstract

A STUDY has been conducted to predict nozzle recession behavior in two different rocket motors and for broad variations of propellant formulations and motor operating conditions. Results show that the recession rate is largely determined by the diffusion of the major oxidizing species (H_2O and CO_2) to the nozzle surface. The free volume in the motor, the concentration of the major oxidizing species as affected by the aluminum content of the propellant, and the chamber pressure exert a strong influence on the recession rate. A correlation to predict the throat recession in terms of the above governing parameters has been developed. This correlation is in good agreement with experimental data in the two different motors considered.

Contents

As the rocket motor operates and propellant exhaust flows through the graphite nozzle, heterogeneous reactions between the exhaust gases and the carbon begin to occur. These reactions deplete the oxidizing species at the nozzle surface and thereby create concentration gradients in the flowfield. These gradients result in the diffusion of oxidizing species to the nozzle surface. Thus, the rate of nozzle recession depends on both the chemical kinetic rates of the heterogeneous reactions and the diffusion rate of oxidizing species to the nozzle surface. Detailed model formulation is given in Ref. 1.

The major oxidizing species considered are H_2O and CO_2; both of which are assumed to react with carbon at the same rate in a first-order reaction[2] to produce CO. The mass-loss rate of carbon due to reaction with component i, $\dot{m}_i$, can be expressed as

$$\dot{m}_i = A_s p_i \exp[-E_a/(R_u T_s)] \tag{1}$$

where the activation energy E_a and the pre-exponential factor A_s are 41.9 kcal/mole and 2470 kg(m^2-s-atm), respectively, as suggested by Libby and Blake.[2] Golovina[3] provides a similar expression for the reaction rate of CO_2 with carbon at high temperatures with E_a and A_s equal to 40.0 kcal/mole and 158 kg/(m^2-s-atm), respectively.

The theoretical model was solved to simulate the operational conditions of both the Bates motor[4] and the Materials Evaluation Research Motor (MERM).[5,6] The input parameters for both the MERM and Bates motor are shown in Tables 1 and 2. Figure 1 shows the effect of aluminum content of propellant on the total recession at the nozzle throat as a function of time. The recession at the throat decreases sharply with increasing aluminum content of propellant even though the flame temperature increases. Chemical kinetics have a significant influence on the recession for the lower aluminum content propellants but their influence diminishes with increasing aluminum content. Also shown in the figure are the experimental data of Swope and Berard.[5] Considering the reproducibility of the experimental data, the agreement between the predicted and experimentally determined recession is well within the experimental variations.

Figure 2 shows the recession as a function of time for five propellants with very different compositions listed in Table 2. The total recession varies almost linearly with time except for propellant 2755R which has a relatively low flame temperature of 2627 K. This results in nozzle surface temperatures of about 2000 K. At these low temperatures, the influence of chemical kinetics is very pronounced. Hence, the predicted recession based on the two different kinetic constants differ by a large value. It is evident from this figure that the recession rate shows no correlation with the flame temperature. However, if the flame temperature is low enough, then the recession process may be strongly influenced by chemical kinetics and one may find a large effect of nozzle material reactivity as well as the flame temperature. The theoretical predictions are compared to the experimental data of Swope and Berard[5] in Fig. 2. Agreement between the predictions and data can be considered reasonable in view of the variation in experimental data for the same propellant.

The preceding discussion has shown that the composition of the propellant plays an important role in determining the recession rate. In particular, the freestream concentrations of oxidizing species H_2O and CO_2 at the nozzle throat appear to be very important. Another important parameter is the chamber pressure. The mass transfer rate of oxidizing species across the boundary layer to the nozzle surface is proportional to the gas-phase density and, hence the pressure. However, at similar pressures and oxidizing species concentrations, the recession rates obtained in the Bates motor are considerably higher than those in the MERM motor.[4,5] This can be explained in terms of the motor configuration and nozzle geometry. The MERM motor, as compared with the Bates motor, has a long flow development length to the nozzle throat, which results in a thicker boundary layer at the throat. The thicker boundary layer presents a greater resistance to the transverse diffusion of oxidizing species to the nozzle surface. This results in a lower recession rate. Also, the diameter of the MERM motor throat is one-fourth that of the Bates motor throat. The greater transverse curvature of the flowfield in the

Table 1 Geometric parameters for simulating MERM and Bates motors

Geometric parameters	MERM	Bates
$R_{\text{throat, inner}}$, cm	0.635	2.54
$R_{\text{throat, outer}}$, cm	2.512	10.00
x_t, cm	25.00	10.25
α, deg	16.7	16.7

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Table 2 Composition of propellant and concentrations of oxidizing species at nozzle throat ($M=1$)

Propellant code	AP, wt. %	Al wt. %	Binder, wt. %	T_f, K	X_{H_2O}	X_{CO_2}
2951	56	36	9PU[a]/9NP[b]	3890	0.096	0.0079
X1	61	20	9.5PU/9.5NP	3788	0.196	0.0207
X5	68	13	9.5PU/9.5NP	3555	0.307	0.0494
X6	73.5	7.5	9.5PU/9.5NP	3348	0.38	0.0914
3003M	30[c]	22.5	7PU/10.5NP	3714	0.041	0.0044
3004	32[d]	18	7.2PU/10.8NP	3651	0.092	0.0117
2865	65	17	17.88PU/0NP	3381	0.154	0.0159
2907	64	17	9.4PU/9.6NP	3691	0.240	0.0305
2755R	76.3	2	20.2PU/0NP	2627	0.331	0.0705
AP/HTPB/Al	80	10	10 HTPB	3426	0.333	0.060

[a]PU = polyurethane. [b]NP = nitroplasticizer. [c]RDX 30 wt.%. [d]RDX 32 wt.%.

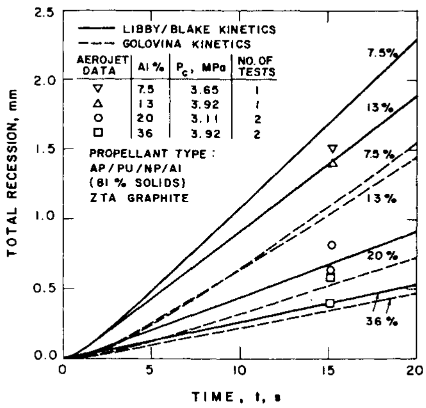

Fig. 1 Effect of aluminum content on nozzle throat recession.

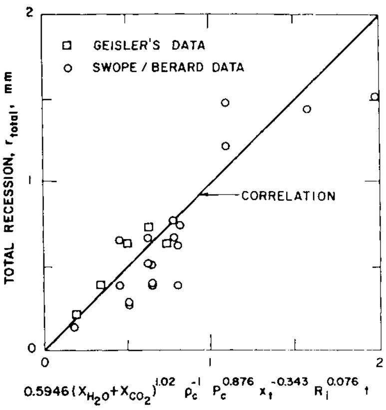

Fig. 3 Comparison of experimental data with correlation.

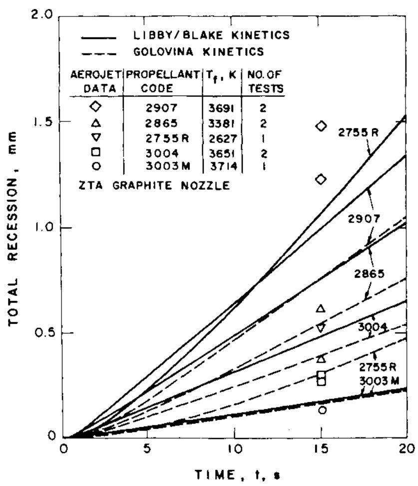

Fig. 2 Comparison of predicted and measured nozzle throat recession for various types of propellants.

MERM motor presents a higher resistance to the diffusion of oxidizing species. Another relevant parameter is the nozzle density since, for the same mass-loss rate, the recession will be inversely proportional to the density.

For rocket nozzle design purposes, it is advantageous to develop a simple correlation for the recession of graphite nozzles. The numerical results of our model have correlated with the following parameters: 1) chamber pressure P_c(MPa); 2) mole fraction of $H_2O(X_{H_2O})$ and $CO_2(X_{CO_2})$ in the freestream; 3) motor operating time, t(s); 4) average entry length from the burning propellant surface to the nozzle throat during the motor operating time period 0 to t (s), x_t (cm); 5) density of the carbon nozzle material, ρ_c(g/cm^3); and 6) radius of the nozzle throat, R_i (cm).

The following correlation for the total recession, r_{total} (mm), as a function of time was obtained:

$$r_{total} = 0.5946(X_{H_2O}+X_{CO_2})^{1.02}\rho_c^{-1}P_c^{0.876}x_t^{-0.343}R_i^{0.076}t \qquad (2)$$

The experimental data of both Geisler[4] and Swope and Berard[5] are plotted in Fig. 3. The 45-deg line represents the above correlation. The agreement between the correlation and the experimental data is close considering the large degree of variation in data obtained under the same operating conditions.

Acknowledgments

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