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Technical Notes

Effect of Surface Roughness and Radiation on Graphite Nozzle Erosion in Solid Rocket Motors

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Nomenclature

h	=	enthalpy
k	=	turbulent kinetic energy
p	=	pressure
p_t	=	chamber pressure
q''_{rad}	=	radiation heat transfer
$\dot{r}_c$	=	net surface recession rate of the nozzle
T	=	temperature
T_t	=	chamber temperature
$\dot{\omega}$	=	species mass production rate
Y_k	=	mass fraction of species k
λ	=	thermal conductivity
ε	=	dissipation rate or emissivity
ρ	=	density

Subscripts

c	=	condensed phase
c-g	=	gas-solid interface
g	=	gas phase
s	=	surface
r	=	radial coordinate
i	=	inner
o	=	outer

I. Introduction

GRAPHITE and carbon–carbon composites, which are widely used as nozzle materials, undergo significant erosion under rocket-motor operating conditions [1,2]. The primary erosion mechanism is a chemical attack by hot combustion products flowing through the rocket nozzle. A comprehensive model was previously established by the authors to predict chemical erosion rates of various nozzle materials, including graphite/carbon–carbon composites [3] and refractory metals [4], over a wide range of chamber pressures. Furthermore, efforts were applied to study the mitigation of nozzle erosion by means of boundary-layer control [5]. Various key mechanisms dictating the nozzle erosion rate propellants have been identified and quantified [3–5]. The most important factors that dictate the erosion process are nozzle surface temperature, concentrations of the oxidizing species, heterogeneous chemical kinetics at the surface, motor operating conditions, and nozzle geometry and material properties.

In this technical note, the theoretical/numerical framework described in [3,4] is extended to take into account the effects of surface roughness and radiation. It is speculated that these two parameters may play some role in determining the nozzle erosion rate. The influence of roughness and radiation on nozzle erosion is studied separately, so that their individual effects can be identified and quantified. Surface roughness may enhance the near-wall turbulence, leading to increase in the local mass and thermal diffusivities. Radiation can alter the overall heat transfer rate to the nozzle wall, thus affecting the nozzle surface temperature and consequently the erosion rate.

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II. Theoretical Formulation

The present study follows the approach employed in [3], and includes the effects of nozzle surface roughness and radiation heat transfer. The formulation involves general conservation equations for the gas phase, radial energy transport in the solid phase, interfacial conditions between the gas and solid phases, and the outer boundary condition of the nozzle material. The numerical method for calculating the net nozzle recession rate remains identical to our previous approach, except modifications in the turbulence transport to accommodate the influence of surface roughness and in the energy balance at the gas–solid interface to account for radiation. Only the modified equations are presented here.

A. Turbulence Closure with Surface Roughness

Nozzle surface roughness modifies the near-wall velocity and turbulence distributions. One of the approaches to treat surface roughness is by using wall-functions, where the numerical solution of the flowfield near the surface is replaced by a local velocity distribution based on the classical semilogarithmic law of wall for a rough surface. The law of wall, however, does not apply for flows involving strong pressure gradients and separation. Patel and Yoon [6] suggested that the extension of two-equation turbulence models has worked well in treating surface roughness. Accordingly, a well-validated two-layer turbulence model [7,8] suitable for transpirating and accelerating flows, adopted in our previous studies [3–5], was modified to include the effect of surface roughness. This approach offers a direct way to extend the k-ε model to rough walls by modifications of the prescribed length scales in the near-surface region. The model employs the standard k-ε two-equation approach for the bulk flow away from the wall (i.e., the outer layer). In the near-wall region (i.e., the inner layer) only k equation is solved. Following the approach described by Patel and Yoon [6], the inner-layer equations are modified to include the effect of roughness in terms of equivalent sand-grain roughness height R_h. The near-wall damping is modeled through specification of modified length scales.

B. Gas–Solid Interfacial Conditions with Radiation

Radiation affects the surface temperature of the nozzle and hence its erosion rate. By taking into account surface radiation, the overall energy balance at the gas–solid interface can be written as

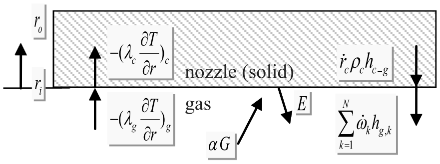

Fig. 1 Schematic of energy balance at gas-solid interface with radiation.

$$\left[\lambda_c \frac{\partial T_c}{\partial r}\right]_{r_i} + \dot{r}_c \rho_c h_{c\text{-}g} + q''_{\mathrm{rad}} = \left[\lambda_g \frac{\partial T_g}{\partial r}\right]_{r_i} + \sum_{k=1}^{N} \dot{\omega}_k h_{g,k} \qquad (1)$$

Figure 1 shows the schematic of energy balance at the nozzle surface. The heat transfer due to radiation is given by

$$q''_{\mathrm{rad}} = (\alpha_s G - E) = \sigma(\alpha_s \varepsilon_g T^4_{g,b} - \varepsilon_s T^4_s) \qquad (2)$$

where $T_{g,b}$ is the bulk gas temperature, G the incident radiation, E the emitted radiation by the graphite surface, α the absorptivity, and ε the emissivity. The value of the Stefan–Boltzmann constant σ is 5.67×10^{-8} W/m^2/K^4.

III. Nozzle Configurations and Inlet Conditions

The physical domain considered in the present study extends from the upstream region of the nozzle throat through its exit, identical to the geometry considered in our previous study [4]. The incoming flow consists of the combustion products of nonmetallized AP/HTPB composite propellants. Table 1 shows the mass fractions of combustion species and flow conditions at the nozzle inlet, along with details of the nozzle geometry. The kinetics data employed for the heterogeneous reactions at the graphite nozzle surface remain the same as those in [3]. The possible increase in chemical reactivity due to surface roughness is not considered in the present study.

The irradiation G on the nozzle surface is considered as diffuse (i.e., independent of angle). The reflectivity and transmittivity from the graphite surface is ignored. To simplify calculations further, graphite is assumed to be a gray surface, implying that the absorptivity and emissivity have the same value ($\alpha_s = \varepsilon_s$) in Eq. (2). They were assumed to be 0.8. The emissivities of individual gas-phase species at a given temperature and pressure were obtained from [9]. The estimated average emissivity ε_g of gases is between 0.1 and 0.4. The upper bound represents the worst-case scenario, although the actual value is likely to be less than 0.4. For a metallized propellant (AP/HTPB/Al), however, the average emissivity is much higher (up to 0.9) due to the presence of alumina particulates.

IV. Results and Discussions

The theoretical/numerical framework described in the preceding sections is implemented to simulate the nozzle erosion in solid rocket-motor environments. At high surface temperature, graphite reacts with oxidizing species of H_2O and CO_2, thereby causing chemical erosion of the nozzle material. Detailed flow and species-concentration fields in the nozzle interior have been discussed in [3,4]. Figure 2 shows the distribution of the baseline chemical erosion rate without including the effect of surface roughness and radiation. The erosion rate is plotted along the length of the nozzle under consideration. It has been shown earlier that the nozzle surface erosion rate correlates well with the heat transfer rate to the nozzle surface [3]. Accordingly, the erosion rate reaches its peak value (0.11 mm/s) near the nozzle throat, due to the maximum heat flux in that region.

Table 1 Rocket nozzle inlet flow conditions[a]

Y_{CO_2}	Y_{H_2O}	Y_{H_2}	Y_{CO}	Y_{HCL}	Y_{N_2}	p_t (MPa)	T_t (K)
0.21	0.28	0.01	0.10	0.29	0.11	5.6	3000

[a]Graphite nozzle density = 1.92 g/cc, throat radius = 0.4 cm, avg. thickness = 3 cm, amb. temperature = 300 K.

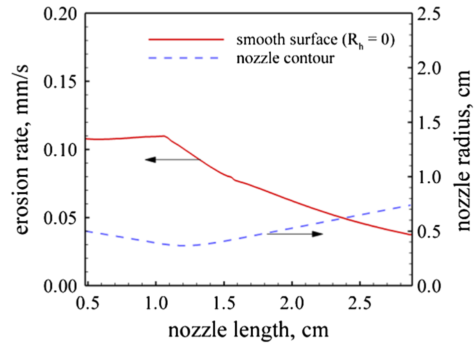

Fig. 2 Baseline nozzle erosion rate for smooth surface without radiation.

The erosion characteristics under the influence of roughness and radiation are treated separately, so that their individual contributions can be identified and quantified. Figure 3 shows the effect of surface roughness on nozzle erosion for a nonmetallized propellant. The equivalent sand-grain roughness R_h is 10 μm. The observed equivalent surface roughness heights of 10–50 μm are typical, as revealed by the postfiring analyses of carbon–carbon composites [10]. The erosion rate at the throat increases to 0.138 mm/s, about 25% higher than its counterpart for a smooth surface. Figure 4 shows the comparison of the heat flux to the nozzle surface for both smooth and rough surfaces. The higher heat transfer for a rough surface can be attributed to enhanced near-wall turbulence, which leads to an increase in effective mass and thermal diffusivities. The surface roughness effect is more pronounced in the region downstream of the nozzle throat. As a consequence, a relatively higher erosion rate is observed as compared with the baseline value. The distribution of the heat transfer rate differs significantly from the baseline counterpart, due to the change of the velocity and thermal boundary-layer profiles when surface roughness is considered.

It is imperative to take into account the effect of surface roughness for long-duration firings because nozzle erosion continues to make the surface rough and even porous. This may result in an elevated

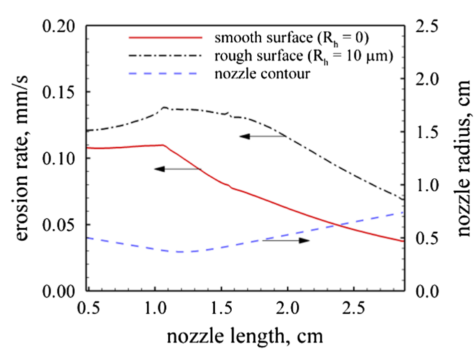

Fig. 3 Comparison of nozzle erosion rate for smooth and rough surfaces; no radiation.

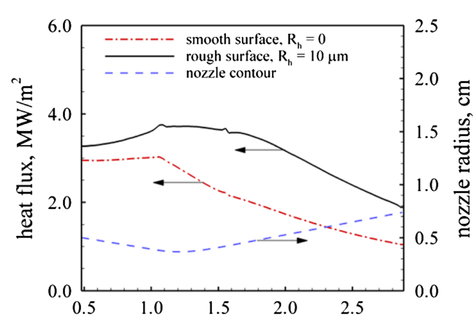

Fig. 4 Comparison of heat-flux to nozzle surface for smooth and rough surfaces; no radiation.

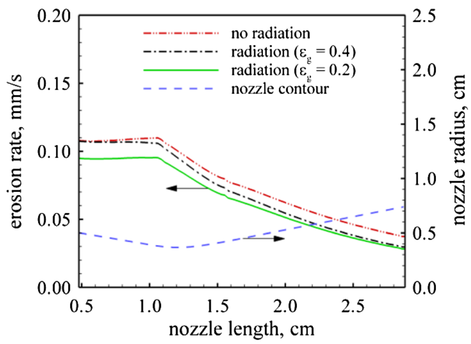

Fig. 5 Comparison of nozzle erosion rate for cases with and without radiation; smooth surface.

erosion rate with time on account of two reasons. First, the increased roughness may further enhance the turbulence level. Second, the porosity could enhance chemical activities of oxidizing species with the graphite material and also weaken the mechanical strength of the nozzle material. The erosion rate will thus keep increasing throughout the rocket-motor operation, and may rise to an alarming level that impacts the thrust performance. It should, however, be noted that the chamber pressure p_t may continue to drop with time with increasing throat diameter and regressive burning surface area. Since the erosion rate is proportional to the chamber pressure [1–4], the decrease in p_t may help counter the increase in the erosion rate due to the increasingly rough and porous surface.

Figure 5 shows the erosion rate profiles with and without considering radiative heat transfer. The surface is treated as smooth. Two different gas-phase emissivities ($\varepsilon_g = 0.2$ or 0.4) are considered for the sake of parametric evaluation. For nonmetallized propellants, which typically exhibit low gas emissivities, the erosion rate decreases with the inclusion of radiation. Figure 5 also shows that the erosion rate increases with increasing gas-phase emissivity. These observations can be explained from the energy-balance equations, Eqs. (1) and (2). The net radiative heat transfer depends on the emissivity and the temperatures of the bulk gas and nozzle surface. Even if the bulk gas temperature is higher than the nozzle surface temperature, a sufficiently low value of ε_g makes q''_{rad} in Eq. (2) negative, implying that the effective radiative heat transfer is from the nozzle toward the gas phase. As the value of ε_g increases, q''_{rad} becomes less negative, bringing the erosion rate closer to the baseline value without radiation. In the upstream region of the throat, the bulk gas temperature is around 2800 K (higher than the nozzle surface temperature $\sim$2300 K), and q''_{rad} is closer to zero. Consequently, the erosion rate is closer to the baseline value. In the downstream region, however, the bulk gas temperature continues to drop to $\sim$2000 K (lower than the nozzle surface temperature of $\sim$2200 K), and q''_{rad} becomes more negative. As a result, the erosion rate is prominently lower than the baseline value.

Figure 6 shows the net heat flux to the nozzle surface for the cases with and without radiation. The results include the contributions from all modes of heat transfer. It is clear that the heat transfer rate

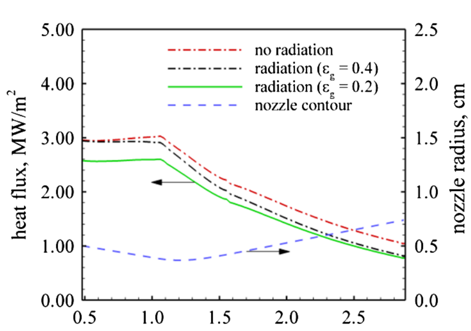

Fig. 6 Comparison of heat-flux to nozzle surface for cases with and without radiation; smooth surface.

Table 2 Comparison of erosion rate at nozzle throat

Case	Erosion rate at throat, mm/s
No radiation, smooth surface	0.11 (baseline value)
No radiation, rough surface ($R_h = 10$ μm)	0.138 (25.45% increase)
Radiation ($\varepsilon_g = 0.2$), smooth surface	0.095 (13.6% decrease)
Radiation ($\varepsilon_g = 0.4$), smooth surface	0.105 (4.5% decrease)

increases with ε_g, when surface radiation is accounted for. The situation with a high ε_g mainly occurs in motors with metallized propellants, where the emissivity of the gas-phase media is enhanced due to the presence of alumina particulates ($\varepsilon \sim 0.8$–0.9). Consequently, the erosion rate is likely to be higher for metallized propellants than its counterpart without radiation. For $\varepsilon_g = 0.2$, the contribution from the radiative heat transfer is about 14% of the convective heat transfer. The change in the erosion rate is about 13.6% from the baseline value, further verifying the correlation between the erosion and heat transfer rates.

For the current nozzle geometry, no experimental data was available for graphite nozzle erosion. The calculated nozzle erosion rates are summarized in Table 2 indicate that surface roughness exerts more significant influence than radiation, and more importantly, in opposite ways for nonmetallized propellants. The results, however, are dependent on the chosen values of gas emissivity ε_g and sand-grain roughness R_h. Since both radiation and nozzle surface roughness are simultaneously present during the motor operation, and since they have opposite effects, the net nozzle-erosion rate may turn out to be close to the baseline value for smooth surface without radiative heat transfer. It will be helpful to quantify the erosion rate for different values of R_h, to obtain a correlation between erosion rate and equivalent sand-grain roughness. Similarly, a correlation of erosion rate with ε_g will also be useful.

V. Conclusions

An integrated theoretical/numerical framework for treating chemical erosion of nozzle materials for nonmetallized propellants has been extended to account for the effects of surface roughness and radiation. The work takes into account propellant chemistry, detailed thermofluid dynamics for a multicomponent reacting flow, energy transport in the condensed phase, heterogeneous reactions at the nozzle surface, and nozzle material properties. A noticeable increase in the erosion rate is observed when surface roughness is considered. This phenomenon can be attributed to the enhanced near-wall turbulence and ensuing increase in mass and thermal diffusivities. It may be crucial to consider surface roughness for long-duration motor firings because nozzle erosion may continue to make the surface rough, thereby resulting in increasing erosion rate with time. The nozzle erosion rate, for nonmetallized propellants, has been found to decrease slightly due to radiation, and the specific change is dependent on the value of the gas-phase emissivity. The present study suggests that surface roughness plays a more significant role, in an opposite way, than radiation in modifying the erosion. Caution, however, must be exercised in making such generalization, as results depend on the chosen values of thermophysical and radiative properties of the nozzle material and gas-phase combustion products.

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