

Coupled Analysis of Flow and Surface Ablation in Carbon–Carbon Rocket Nozzles

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A study is conducted to predict carbon–carbon nozzle recession behavior in solid rocket motors for wide variations of propellant formulations and motor operating conditions. The numerical model considers the solution of Reynolds-averaged Navier–Stokes equations in the nozzle, heterogeneous chemical reactions at the nozzle surface, variable transport and thermodynamic properties, and heat conduction in the nozzle material. Results show that the ablation rate is largely determined by the diffusion of the major oxidizing species (H₂O, CO₂, OH) to the nozzle surface. Both the concentration of the major oxidizing species (affected by the aluminum content of the propellant) and the chamber pressure exert a strong influence on the ablation rate: it increases almost linearly with chamber pressure and it decreases with increasing aluminum content of propellants. The calculated results show an excellent agreement with the experimental data from the ballistic test and evaluation system motor firings.

Nomenclature

A	=	cross-section area, m ²
D_{im}	=	effective diffusion coefficient, m ² /s
h	=	enthalpy, J/kg
k	=	thermal conductivity, W/m · K
Le	=	Lewis number
M	=	Mach number
\dot{m}	=	mass blowing rate per unit area, kg/m ² · s
N_c	=	number of species
N_{el}	=	number of elements
p	=	pressure, N/m ²
r	=	distance from surface, m
\dot{s}	=	erosion rate, m/s
T	=	temperature, K
t	=	time, s
u	=	streamwise velocity, m/s
v	=	velocity component normal to surface, m/s
W	=	molecular weight, kg/kmole
Y	=	elemental mass fraction
y	=	mass fraction
y^+	=	dimensionless wall distance
α_{ki}	=	mass fraction of element k in species i
ΔH_{abl}	=	heat of ablation, J/kg
η	=	outward coordinate normal to surface
μ_t	=	turbulent viscosity, kg/m · s
ρ	=	density, kg/m ³

Subscripts

c	=	combustion chamber
i	=	species

k	=	element
s	=	solid (carbon) properties at gas–solid interface
t	=	throat
w	=	gas properties at gas–solid interface

I. Introduction

WITH the development of high-energy solid propellants and harder firing conditions in advanced solid rocket motors (SRM), carbon–carbon (C/C) materials have found increasing application in SRM nozzles because of their excellent thermal and physical properties and low densities. But in spite of these advantages, the C/C nozzle surface recedes because of the chemical attack by the exhaust gases increasing the nozzle throat area and resulting in a nominal performance loss. The identification and description of the major mechanisms governing the nozzle erosion has been the subject of many investigations [1–10] in solid rocket technology. The models developed to predict the nozzle erosion in the 1960s and 1970s, when limited computational resources were available, included necessarily simplifying assumptions because a complete model should take into account numerous parameters: solid-propellant composition, motor operating conditions, duration of firing, nozzle geometry and material properties, geometric and thermal history of the nozzle, rates of diffusion of the species through the boundary layer, and heterogeneous chemical reactions with the surface material.

Erosion is a direct consequence of the fact that, as the propellant of the rocket motor burns, the C/C nozzle wall is exposed to the hot exhaust gas and its surface temperature increases. At high surface temperatures, heterogeneous chemical reactions begin to occur between the nozzle material and the oxidizing species present in the exhaust gas, resulting in the thermochemical erosion of the nozzle. Many researchers [1,7–12] have concluded that the most reactive gases are those that react with carbon to form carbon monoxide, such as H₂O, CO₂, and OH, normally found in a significant amount in the exhaust gas. In particular, Swope and Berard [1] found a direct correlation between the nozzle erosion and the total concentration of the oxidizers capable of forming CO with the graphite and showed that H₂O is the major contributor to nozzle erosion. Heterogeneous reactions consume the oxidizing species at the nozzle surface and thereby create species concentration gradients in the boundary layer that result in the diffusion of oxidizing species to the nozzle surface. Thus, the erosion rate will depend on both the diffusion rate of oxidizing species across the boundary layer to the wall and on the chemical kinetic rates of heterogeneous reaction at the surface, as shown by a simple model for the erosion of graphite throat nozzles developed by Delaney et al. [2]. The lowest rate process will control

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