Journal of Propulsion and Power
Vol. 25, No. 5, September–October 2009

Mitigation of Graphite Nozzle Erosion by Boundary-Layer Control in Solid Rocket Motors

Piyush Thakre[*] and Vigor Yang[†]
Pennsylvania State University, University Park, Pennsylvania 16802

DOI: 10.2514/1.41293

A comprehensive analysis is performed to study the mitigation of graphite nozzle erosion in solid rocket motors loaded with nonmetallized ammonium perchlorate/hydroxyl-terminated polybutadiene composite propellants. The work extends our earlier model for predicting the chemical erosion of nozzle materials to include a nozzle boundary-layer control system. The strategy involves injection of relatively low-temperature species, obtained from reactions of an ablative material (succinic acid/polyvinyl acetate) and a small amount of propellant combustion gases, to a location slightly upstream of the nozzle throat. The formulation takes into account the detailed thermofluid dynamics of a multicomponent reacting flow, heterogeneous reactions at the nozzle surface, and condensed-phase energy transport. The effect of nozzle boundary-layer control system injection on the near-surface physiochemistry is investigated. Various fundamental mechanisms dictating the effectiveness of the nozzle boundary-layer control system are identified and quantified. The calculated erosion rates with the nozzle boundary-layer control system are negligible for the vertical injection, even at ultrahigh pressures. The mitigation of nozzle erosion is attributed primarily to the low temperature of the injected fluid, and secondarily to the reduced concentrations of oxidizing species, H_2O, CO_2, and OH, near the nozzle surface. A parametric study is also conducted to determine the influence of such nozzle boundary-layer control system operating parameters as temperature, velocity, and injection angle.

Nomenclature

A_i = preexponential factor for rate constant in reaction i
b_i = temperature exponent for rate constant in reaction i
E_i = activation energy for reaction i
$\dot{m}$ = mass flow rate
p = pressure
p_t = chamber pressure
R = particular gas constant
Re = Reynolds number
R_u = universal gas constant
r = radial coordinate
T = temperature
T_{inj} = injection temperature
T_t = chamber temperature
$u_{r\text{-inj}}$ = nozzle boundary-layer control system injection velocity
x = axial coordinate
Y_i = mass fraction of species k
θ_{inj} = angle of nozzle boundary-layer control system injection
$\dot{\omega}$ = species mass production rate

Subscripts

div = diverted
inj = injection
pyro = pyrolysis
s = surface

I. Introduction

THE erosion of a rocket-nozzle throat during motor operation leads to several problems. The material erosion reduces the area ratio of the nozzle exit to the throat, and consequently decreases the propulsive efficiency of the vehicle. The nozzle surface recession rate should be accounted to accurately predict the performance of a rocket motor. Graphite and carbon–carbon composites, which are widely used as nozzle materials, undergo significant erosion at high chamber pressures and temperatures [1–3]. The surface recession is primarily due to the chemical erosion caused by heterogeneous reactions between the nozzle material and oxygen-containing species (e.g., H_2O, OH, and CO_2) in the propellant combustion products. Several comprehensive models [4–6] have been established to predict the nozzle erosion in practical rocket-motor environments. The erosion rate was found to increase linearly with the chamber pressure. Because a throat-area increase of more than 5% is considered alarming for most propulsion applications, the erosion level for ultrahigh pressures ($\sim$50 MPa) and long-duration firings can become unacceptable. It is thus crucial to devise methods to mitigate nozzle throat erosion over a wide range of operating conditions, especially at high pressures.

One approach to reducing erosion is to develop propellants that yield minimal concentrations of undesirable oxidizing species. This may, however, not be practical from the perspective of system implementation in the near term. It is known that the chemical erosion of a nozzle can also be lowered by increasing the aluminum (Al) content in a metallized ammonium perchlorate/hydroxyl-terminated polybutadiene (AP/HTPB) propellant [2]. But the resultant increase in alumina slag ($Al_2O_{3(l)}$) may reduce the delivered performance of the motor, due to thermal and momentum-lag losses associated with two-phase flow. The overall combustion efficiency may also decrease, leading to some unburnt Al. In addition, there would be an increase in mechanical erosion due to impingement of condensed-phase Al_2O_3 particulates on the nozzle surface, especially for submerged nozzles. Refractory metals such as tungsten, rhenium, molybdenum, and their alloys have been used as materials for nozzle inserts, because they can resist chemical erosion more effectively than carbon-based materials [6,7]. Unfortunately, the cost and weight penalties associated with these metals may sometimes render their use uneconomical. Refractory ceramic materials have also been employed, due to their remarkable erosion resistance. Although ceramics present lesser weight penalties than refractory metals, they are known to

---

Received 28 September 2008; accepted for publication 6 June 2009.

[*] Ph.D. Candidate, Department of Mechanical and Nuclear Engineering; pkt109@psu.edu.

[†] John L. and Genevieve H. McCain Chair in Engineering, Department of Mechanical and Nuclear Engineering; currently Georgia Institute of Technology; vigor.yang@aerospace.gatech.edu. Fellow AIAA.