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Title

Study of SRM Nozzle Divergent Performance Improvement Under Fixed Geometrical Constraints

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Abstract

This paper analyzes the possibility of improving the performance of a solid rocket motor through the redesign of its nozzle divergent profile, by keeping the same nozzle length and increasing its area ratio. The third stage motor of Vega and Vega-C, namely Zefiro 9, has been used as study case for the present work. Under ideal conditions, the increase of the vacuum specific impulse is a direct consequence of an increase of the nozzle area ratio. In real conditions, increasing the expansion ratio at fixed nozzle length also increases the divergence losses, because of the higher divergence angle at the nozzle exit. Hence, an optimal design shall be looked for [1]. Furthermore, viscous losses, losses associated with nozzle throat erosion [2,3,6] and two-phase flow losses [4,5] shall also be assessed with respect to the nominal (reference) nozzle configuration to quantify the potential performance gain of the redesigned configurations more accurately. The analysis is divided into five major parts:

i) In the first part, a zero-dimensional (0D) quasi-steady internal ballistics model for the reconstruction of solid rocket motor performance is adopted to assess the vacuum specific impulse increase of the motor with respect to the nozzle area ratio increase and how it is affected by the variation of the non-ideal parameters.

ii) In the second part, a thorough parametric analysis is performed via CFD tools to assess the role of nozzle divergence losses and to select novel nozzle divergent designs that show potential gains with respect to the nominal configuration [7,8]. In this part, CFD simulations are performed assuming inviscid, constant-gamma, and single-phase (zero-velocity lag and zero-thermal lag) flow to assess how the three major nozzle parameters (i.e., divergent inlet angle, divergent exit angle, and nozzle expansion ratio) are affecting the performance and to analyze in detail the competition between divergence losses and expansion ratio at fixed nozzle length.

iii) In the third part, once divergence losses have been assessed, viscous and variable-gamma simulations are performed to assess the secondary role exerted by both viscosity and variable-thermodynamic properties in the expansion process. The optimal nozzle profiles obtained in the previous part are eventually modified accounting for these second-order effects. Moreover, alternative nozzle profiles with increased lengths with respect to the nominal configuration are also proposed and analyzed.

iv) In the fourth part, the effects of nozzle erosion [6] are assessed for the different optimized configurations and the performance gains are analyzed in detail at different stages of the erosion process from 0% (motor ignition) to 100% (motor burn-out) nozzle erosion.

v) Finally, in the last part, the single-phase assumption is removed and two-phase flow simulations including momentum and energy lag [9] between alumina particles and the combustion gases expanding in the nozzle are performed for the different optimized configurations and considering different values of particle diameters [10,11]. Two-phase flow

simulation results are presented to assess both the impact of gas-particle momentum/thermal lag on the performance gains of the redesigned nozzles for various particle diameters and the potential risk of particle impingement with the nozzle divergent wall in the supersonic acceleration process.

References

[1] Wong, E. Y. Solid rocket nozzle design summary: Solid rocket nozzle design, discussing configuration, material selection and aerodynamic, thermodynamic and stress analysis. Propulsion Joint Specialist Conference (June 1968).

[2] Bianchi, D. & Nasuti, F. Carbon-Carbon Nozzle Erosion and Shape-Change Effects in Full-Scale Solid-Rocket Motors. Journal of Propulsion and Power 28, 820–830 (2012).

[3] Cavallini, E., Bianchi, D., Favini, B., Di Giacinto, M. & Serraglia, F. Internal ballistics modeling of high performance SRMs with coupled nozzle erosion characterization. 47th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, 5799 (2011).

[4] Li, Z., Wang, N., Shi, B., Li, S. & Yang, R. Effects of particle size on two-phase flow loss in aluminized solid rocket motors. Acta Astronautica 159, 33–40 (2019).

[5] Bailey, W., Nilson, E., Serra, R. & Zupnik, T. Gas particle flow in an axisymmetric nozzle. Ars Journal 31, 793– 798 (1961).

[6] Bianchi, D., Nasuti, F. & Onofri, M. Radius of curvature effects on throat thermochemical erosion in solid rocket motors. Journal of Spacecraft and Rockets 52, 320–330 (2015).

[7] Sutton, G. & Biblarz, O. Nozzle theory and thermodynamic relations. Rocket propulsion elements, 75–82 (2001).

[8] Davis, D. Investigation of optimization techniques for solid rocket motor nozzle contours. 18th Joint Propulsion Conference, 1188 (1982).

[9] Kliegel, J. R. & Nickerson, G. R. Flow of gas-particle mixtures in axially symmetric nozzles. Detonation and two phase flow, 173 (1962).

[10] Salita, M. Modern SRM Ignition Transient Modeling (Part1): Introduction and Physical Models in. 37th Joint Propulsion Conference, Salt Lake City, UT (July 2001).

[11] Hermsen, R. Aluminum Oxide Particle Size for Solid Rocket Motor Performance Prediction. Journal of Spacecraft and Rockets 18, 483–490 (1981).