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Analysis of Ignition and Flame Spreading in Solid Rocket Motor Star Slots

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Introduction

THE ignition transient of a solid rocket motor (SRM) employing a pyrogen igniter can be defined as the time interval from the onset of the igniter flow to the time a quasi-steady flow develops. A little-understood portion of the starting transient for (star) slotted head-end grain configurations is the time interval encompassing the initiation of the igniter flow, the first appearance of a flame on the star grain, and the subsequent flame spread over the star slot region.

Previous analyses[1–7] for motors such as those used on the Space Shuttle agree quantitatively well with test data, except for the time period that directly involves burning of the head-end star grain segment. Discrepancies during this time period are believed to arise from three factors: 1) the flowfield is assumed to be one-dimensional, 2) the star geometry in the head-end segment is approximated by variations in port area and grain burning perimeter, and 3) the igniter flowfield is not accounted for.

The authors have previously presented a numerical calculation method utilizing the time-dependent, two-dimensional Navier–Stokes equations, which calculates the subsonic flow induced in the slot by the supersonic igniter plume.[8] The focus of the present study is the calculation of the initial portion of the ignition transient, beginning with the start of igniter flow and ending when the head-end star slot segment of the motor is fully burning. The expanding igniter plume, the complex flow patterns within the star slot, heat transfer to the propellant grain, and subsequent propellant burning are considered.

Analysis

The geometry considered is that of the Space Shuttle SRM, consisting of a head-end, star slot segment and three long circular port (CP) grains. Flow in the head-end slot region is assumed to be two dimensional, whereas that in the downstream CP region is assumed to be axisymmetric. As shown in Fig. 1, several planes of symmetry exist in the head end, corresponding to the number of slots. Reference 8 presents the full set of governing equations, including appropriate source terms due to propellant burning in both the slot and CP regions. The igniter exit parameters at the condition of maximum igniter mass flow are taken as reference values. The distance from the motor centerline to the bottom of the slot is taken as the reference length.

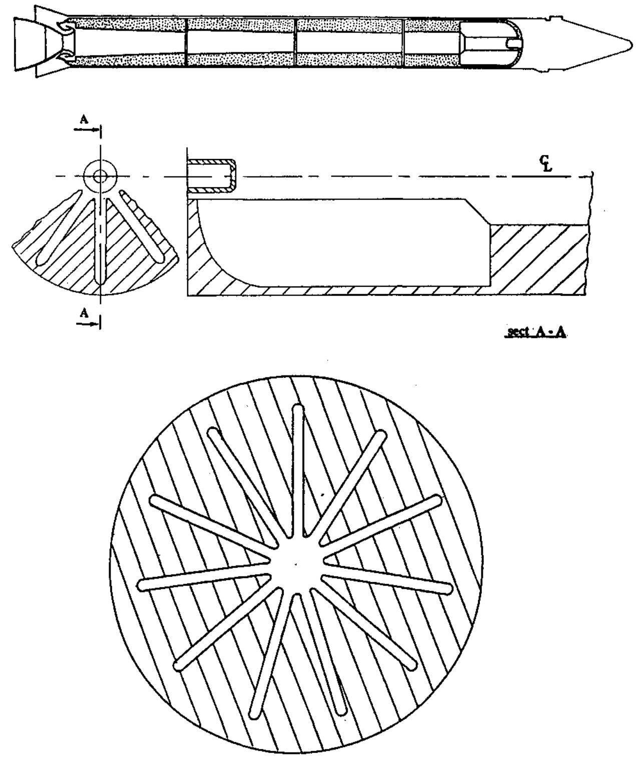

Fig. 1 Geometry of the Space Shuttle SRM star slot.

The purpose of the present analysis is to present a methodology for examination of the interaction between the igniter plume, the developing flowfield within the head-end star grain slots, and the rate of flame spread over the grain surface. Both convective and radiative heat transfer to the propellant grain surface are considered. The convection model utilizes a correlation developed by Kays and Leung,[9] used previously to correlate heat transfer within the O-ring gap of the Space Shuttle nozzle-to-case joint,[10] given by

$$Nu = \frac{0.152Re^{0.9}Pr}{0.833[2.25 \ln(0.114Re^{0.9}) + 13.2Pr - 5.8]} \tag{1}$$

where the Reynolds number is based on the hydraulic diameter of a single star grain slot. Comparison of the predictions of this correlation with cold-flow experimental data taken in a one-tenth scale model of the Space Shuttle head-end slot is given in Ref. 10. Following Johnston,[7] we consider only segments of the propellant grain that lie adjacent to burning propellant, assume that the propellant surface absorbs and the flame emits perfectly, and utilize a shape factor of 0.5 for the unignited adjacent segment. This results in the following expression for the radiative heat transfer coefficient:

$$h_r = (\sigma/2)(T^2_{\text{flame}} + T^2_{\text{wall}})(T_{\text{flame}} + T_{\text{wall}}) \tag{2}$$

where σ is the Stefan–Boltzmann constant and T_{flame} is the flame temperature. The propellant burning rate is taken as

$$r = r_{\text{ref}}(p/p_{\text{ref}})^n \exp[\sigma_p(T_{p_i} - T_{\text{ref}})] \tag{3}$$

The grain is considered to be a semi-infinite slab whose temperature is initially uniform. Heat transfer to the slab from

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the hot gas is assumed to be one dimensional. Burning commences when an element of the propellant surface reaches a critical ignition temperature (850 K).

As noted in Ref. 8, the numerical solution of the equations of motion is obtained utilizing the explicit, time-dependent, predictor–corrector finite difference method developed by MacCormack.[11] An explicit fourth-order numerical dissipation scheme[12] has been introduced into the set of equations to damp numerical oscillations induced by the severe gradients in the flowfield associated with the developing igniter flow.

The full set of initial and boundary conditions is discussed in Ref. 8. Of primary importance is the specification of the time variant conditions from the developing igniter flow at the inflow boundary of the calculation domain. The conditions specified are those from the single-port igniter used in the Space Shuttle SRM. The values of the flow variables u, ρ, p, and T at the igniter nozzle exit are calculated using one-dimensional nozzle flow theory. The outflow boundary at the aft end of the motor is imposed by assuming that a diaphragm exists at the motor exit. When the pressure differential across the diaphragm reaches some nominal value, e.g., 1 atm, the diaphragm bursts. The nozzle is assumed to fill instantaneously. A simple one-dimensional time-dependent mass conservation calculation is then utilized to provide boundary conditions for the next time step.

Results

Propellant ignition is assumed to occur when the temperature of the surface reaches a critical ignition temperature (850 K). Figure 2 compares the calculated head-end pressure vs time trace with values obtained from measurements taken from an actual motor firing[13] as well as with values calculated from a typical $P(x, t)$ one-dimensional model.[5] Note that the one-dimensional model overestimates the lag time between the onset of igniter flow and the beginning of pressurization in the head-end region. At later times, the one-dimensional model overestimates the rate of pressure rise in this region. The effect of radiation is apparent in the two curves shown for the two-dimensional calculations within the slot. The initial pressure rise is predicted here, but the later rise rate is underestimated.

Figure 3 illustrates the predicted burn sequence within the star slot, where burning propellant is represented by the lighter surface color. First ignition of the propellant surface occurs at ~24 ms (measured from the onset of igniter flow) near the barrel shock located in the igniter plume, as might be expected. As in the one-dimensional case, first ignition of the downstream CP grain occurs at ~115 ms, when approximately 54% of the star grain is burning. Approximately 90% of the star region is burning after 200 ms.

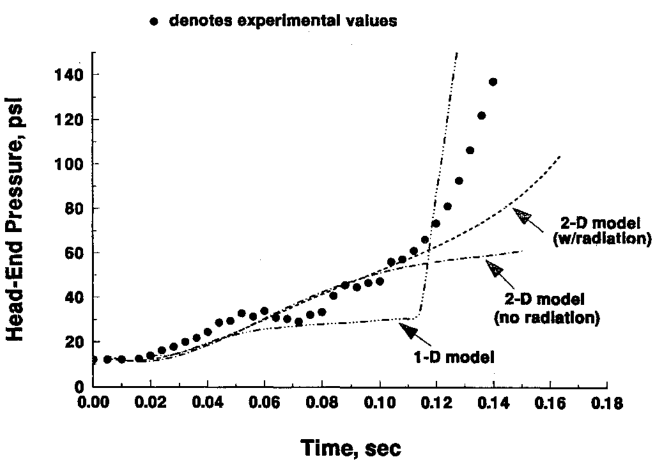

Fig. 2 Ignition transient head-end pressure rise comparison.

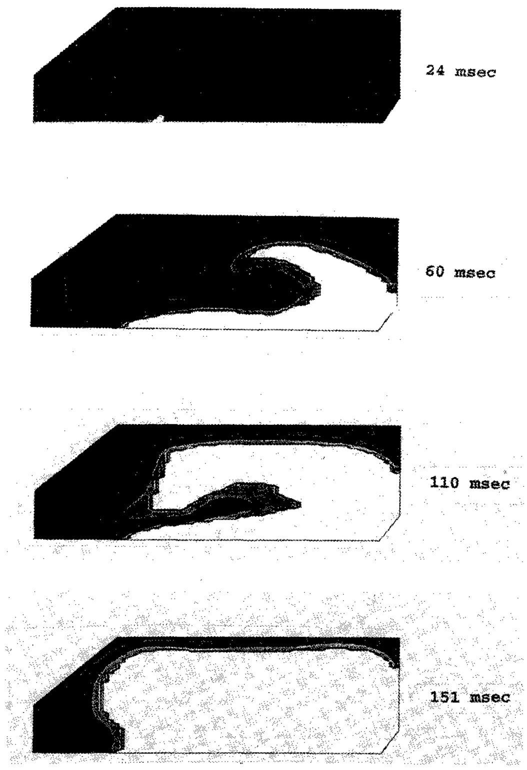

Fig. 3 Predicted star slot burn sequence.

Summary and Conclusions

A model to analyze the unsteady, two-dimensional compressible flow in the head-end, star slot region of a solid rocket motor during the portion of the ignition transient from igniter firing to full burning of the star slot is presented. The interactions between the igniter plume, the flowfield within the slot, heat transfer to the propellant, and subsequent flame spreading are considered. The heat transfer model is a one-dimensional time-dependent conduction analysis for the grain coupled with a convection/radiation model for heat transfer from the igniter gases to the grain.

The two-dimensional model presented here predicts the observed Space Shuttle SRM pressure rise quite well for the first 100 ms after (pyrogen igniter) ignition. It subsequently underestimates the pressure rise-rate, at which time radiative heat transfer to the propellant grain becomes significant. This suggests that better modeling of the heat transfer mechanisms (radiation in particular) could lead to better correlation with observed data.

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