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Studies on Starting Transient in Solid Rockets

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ABSTRACT

Accurate description of starting transient history allows and justifies the use of small margin of safety for the engine parts, resulting in high motor mass ratio in addition to satisfying the control and guidance requirements of the vehicle. Studies have been carried out for the prediction and reduction of ignition peak and pressure-rise rate during the starting transient of solid rocket motors. Numerical studies have been carried out using a two dimensional Navier-Stokes solver. It has been inferred through the parametric studies that, in the case of solid rocket motors with uniform port, high ignition peak is observed at high spread rate and low pressure-rise rate. In the case of the port with sudden expansion configuration, high ignition peak is observed at relatively high average spread rate and high-pressure rise rate. These studies are expected to aid the designer in reducing the ignition peak by altering the propellant properties or igniter characteristics without sacrificing the motor performance.

1. Introduction

Although technology in the solid propellant field has advanced significantly over the past sixty years, there are still many unresolved problems [1-4]. In an attempt to resolve some of these problems and in the light of new findings, a substantial revision of the existing ideas may be necessary. One such problem of urgency is the starting transient/ignition transient predictions for the solid rocket motors (SRMs) having non-uniform port configurations [5-8].

Ignition transient is usually, defined as the time interval between the application of the ignition signal and the instant at which the rocket motor attains its equilibrium or designed operating conditions. It can be generally considered to consist of three intervals, namely the induction period or ignition delay, the flame spread period and the chamber filling period. All these three phases are beset with several uncertainties, which make the overall starting transient a very complex problem.

The two primary concerns during the starting transient are the overall time of the transient and the extent of the pressure rise (ignition peak). The overall time, that is, the delay in the development of full thrust must be kept within some limit and must be reproducible. The ability to predict and control the motor transient enables the following

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mportant design and analysis objectives:- 1)prediction and reduction of overpressure and ›ressure rise rate, (2) predicting how a design nodification will alter performance (propellant substitution, changes in throat area and motor limensions, propellant treatment, etc.).

The above-mentioned objectives necessitated the starting transient study in detail so as to predict he thrust transient of any motor with confidence. t has been reported that, the results from the existing models were inconclusive as to the cause of high-pressure rise rate encountered in the Space Shuttles redesigned solid rocket motor (RSRM) han in any of the Titan solid rocket motors [2,4].

Even though the previous studies have been ıelpful in interpreting many fundamental processes on ignition transient, the understanding of ignition spike in solid rocket motors with non-uniform ports has been elusive. This calls for a eexamination of all the available information before embarking on the formulation of a new nodel and a code of solution. Towards this objective, studies on starting transient in solid ocket motors have been undertaken.

2. Methodology

In solid rockets with sudden expansion regions, teep divergences or protrusions in the port, it is 'ery likely that flow separation would take place t transition locations during the flow of igniter gases or gases evolved by partially ignited propellant surface. Among all elemental processes of ignition transient, it is necessary to identify the ole of flame spread through a solid rocket motor vith non-uniform port before embarking to the ormulation of a new model and a code of olution. Towards this end, initially it was ypothesized that flow separation and reattachment vould cause secondary ignition at a downstream

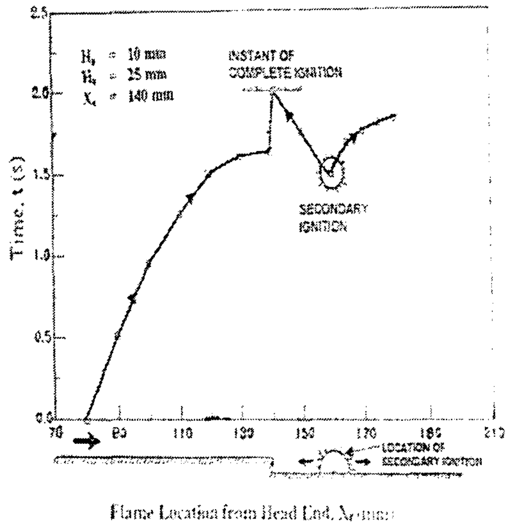

Fig. 1 Case of backward flame spread at higher pressure (peak pressure=12.6Ksc).

point followed by backward spread of the flame in addition to normal forward spread. For proving these hypothesis, successful experimental and theoretical studies have been carried out in solid rocket motors and reported earlier and reviewed here. An idealized two dimensional laboratory-size solid propellant window motor has been devised for studying the flame spread pattern through sudden expansion ports with the help of a high-speed cine photography [5, 6].

Figure 1 shows a typical experimental result with secondary ignition and multiple flame fronts. Numerical simulation of the flame spread has been carried out with the help of a Navier-Stokes solver. Through the experimental and theoretical investigation the concept of secondary ignition and formation of multiple flame fronts has been proved conclusively [5-8].

Further, the role of the nature of flame spread on pressure and pressure-rise rate during starting transient of solid rocket motors has been investigated with the help of a theoretical model.

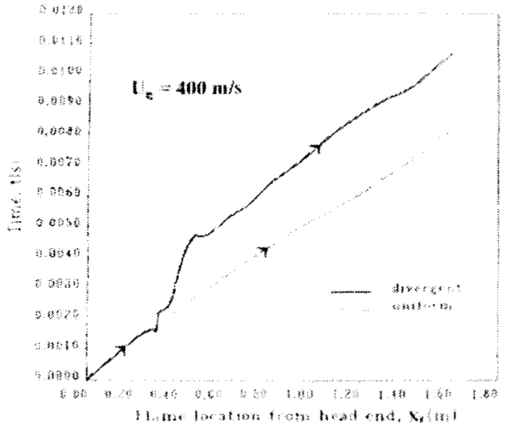

Fig. 2 Numerical prediction of the location of flame fronts at different intervals is showing the variation of flame spread in two different port geometries but with the same inflow conditions and propellant properties

In this model, the unsteady heat conduction equation for the unignited propellant grain is solved together with the governing equations for gas phase to obtain the following ordinary differential equation for the evaluation of propellant surface temperature,

$$\frac{dT_{ps}}{dt} = \frac{4\alpha_{pr} q_w^2 (T_g - T_{ps})}{3\lambda_{pr}^2 (T_{ps} - T_{pi})(2T_g - T_{ps} - T_{pi})} \quad (1)$$

where q_w is evaluated from the code.

3. Numerical Method of Solution

Numerical studies have been carried out with the help of a two-dimensional code. This code solves unsteady Reynolds-averaged thin-layer Navier-Stokes equations by an implicit LU-factorization time-integration method. It uses the state-of-the-art numerical methods like upwind differencing with Van Leer flux-vector splitting, which are necessary for getting good quality time accurate solutions for practical configurations. The system of governing differential equations with

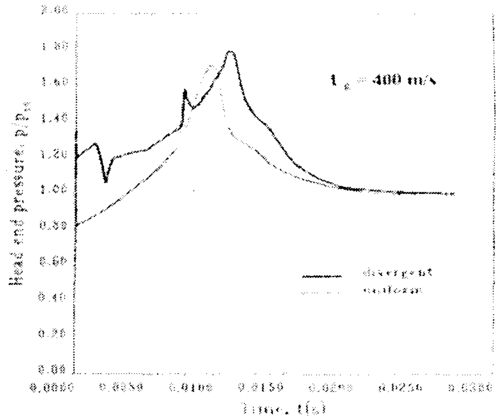

Fig. 3 Comparison of ignition peak and overall pressure transient history at the head-end of SRMs with two different port geometries but with the same inflow condition and propellant properties.

boundary conditions is solved using the finite volume method. An algebraic grid-generation technique is employed to discretize the computational domain. Grid system (320 x 80) in the computational region is chosen.

A constant igniter gas flow is assumed as the inflow condition. Initial propellant surface temperature is prescribed. At the solid walls, no-slip boundary condition is imposed and pressure is calculated from the momentum equations. The ignition criterion, adopted in this analysis, is that a point on the propellant surface ignites when it attains the prescribed ignition temperature. The model describes thus the process of flame spreading along the propellant surface, which starts at first ignition and ends when the entire surface is ignited. The solution is obtained by solving the Eq.(1) simultaneously with the governing equations for gas phase to yield the propellant surface temperature at any calculated time and position. Using this model, several test runs have been made with different port geometries and inflow conditions.

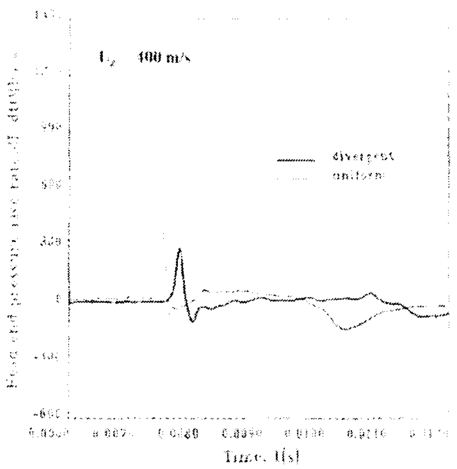

Fig. 4 Comparison of head-end pressure rise rate of SRMs with divergent and uniform port (corresponding to Fig. 3).

4. Results and Discussion

The numerical prediction of the location of flame fronts corresponding to the experimental configuration and propellant properties has reproduced many qualitative features such as secondary ignition and multiple flame fronts. The case of uniform port is considered as the base for comparing the non-uniform port cases. Inflow conditions, propellant properties, length to diameter ratios are the same in both cases. In relation to the uniform port case, this case with higher K (the ratio of burning surface area to nozzle throat area) would lead to lower equilibrium chamber pressure (P_{eq}), but the discussion below will be based on the non-dimensional pressure ratio (P/P_{eq}). At these conditions, the location of the flame-front at different intervals of time in a divergent and uniform port is compared in Fig. 2.

In both the cases initial spread rate is found to be nearly constant. The effect of mass addition is more pronounced in narrower ports and hence the uniform port case exhibits the higher flame spread rate. Among the two, the case with divergent port took more time for the complete ignition of the propellant surface. Figure 3 shows the comparison of the corresponding starting transient history of the above two cases. With the same propellant properties and inlet velocity, significant variation in ignition peak and pressure-rise rate is observed in these motors.

Figure 4 compares the pressure-rise rate of the above two cases. At the aforementioned conditions, high pressure-rise rate at the head-end is observed in uniform port case rather than in the non-uniform port (divergent) case. The results from the parametric study indicate that when the port is narrow there is a possibility of an increase in pressure rise rate due to relatively high spread rate. Hence it appears that high-pressure rise rate at the head end of the practical port configurations correlates with the flamespread rate, as a result of the propellant grain configuration.

The above results on flame spread rate vis-à-vis $(dP/dt)_{max}$ should be viewed in the right perspective. Here the pressure-rise rate discussion has come in because of the observations made in the introduction with regard to RSRM and Titan configurations [4]. This factor $(dP/dt)_{max}$ has structural implications in addition to the possibility of giving rising to transient burn rate effects which is, however, not considered in the present model.

5. Conclusions

A critical factor that is an outcome of this internal flow simulation is the accurate description of surface heat flux, which dictates the flame spread process. These studies have made it possible to examine a number of factors, which are important in the starting transient studies of solid rockets with non-uniform ports. These studies are expected to aid the designer in reducing the ignition peak by altering the propellant properties or igniter characteristics without sacrificing the motor performance.

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