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Technical Notes

TECHNICAL NOTES are short manuscripts describing new developments or important results of a preliminary nature. These Notes should not exceed 2500 words (where a figure or table counts as 200 words). Following informal review by the Editors, they may be published within a few months of the date of receipt. Style requirements are the same as for regular contributions (see inside back cover).

Starting Transient Flow Phenomena in Inert Simulators of Solid Rocket Motors with Divergent Ports

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Introduction

THE basic idea behind a solid rocket motor (SRM) is simple but its design is a complex technological problem requiring expertise in diverse subdisciplines to address all of the physics involved. The design optimization of high-performance rockets is more complex when the mission demands dual thrust. The motivation for the present study emanates from the desire to explain the phenomena or mechanism(s) responsible for the high ignition peak pressure (pressure peak), pressure-rise rate, instabilities, and pressure oscillations often observed during the static tests and the actual flights of certain class of high-performance SRMs with nonuniform ports [1–9]. In the SRM industry many dual-thrust motors (DTMs) are known to have experienced abnormal high ignition peak pressure often on the order of 5 times the steady state value [6]. Various measures were taken to eliminate the peak pressure, but none of the conventional remedies seemed to help. Nevertheless, through the empirical techniques increasing the port area of the motor has been proposed as one of the remedies for reducing the unusual ignition peak of the DTM. Although such a remedy could negate the unacceptable peak pressure, it has affected the high-performance nature of the motor. Hence the elimination of the unusual ignition peak and the pressure-rise rate without sacrificing the basic grain configuration or the volume loading became a meaningful objective for further studies.

It has been shown conclusively through the previous experimental and numerical studies on flame spread with sudden expansions of ports of SRMs that under certain conditions, secondary ignition can occur far downstream of the port [7]. One secondary ignition would result in two additional flame fronts, one spreading forward and the other backward. The effective time required for the complete burning surface area to be ignited comes down drastically giving rise to the high pressurization rate (dP/dt) in the second phase of the ignition transient. Having logical precise relevance to the matter at hand, the next step through this Technical Note will be to examine the intrinsic flow physics actuating the flow separation and secondary ignition in high-performance SRMs with a nonuniform port.

Overview of the Numerical Methodology

Numerical simulations have been carried out with the help of a well-established two-dimensional standard k-omega model. This code solves standard k-omega turbulence equations with shear flow corrections. In the numerical study, a fully implicit finite volume scheme of the compressible, Reynolds-averaged, Navier–Stokes equations is employed [8,9]. The viscosity is determined from the Sutherland formula. The initial wall temperature, inlet total pressure, and temperature are specified, which are in terms of pressure relative to the operating pressure. At the solid walls a no-slip boundary condition is imposed. At the nozzle exit a pressure profile is imposed. The transient mass additions due to propellant burning are deliberately suppressed in this study to examine the separated and reattached flow features discretely in SRMs with nonuniform ports. The baseline values are selected based on typical motor configurations. In this Note, instead of a conventional numerical study, diagnostic investigation is carried out to examine the intrinsic flow physics pertinent to separation and secondary ignition in inert (unignited) simulators of SRMs with nonuniform ports.

Results and Discussion

In the first phase low-velocity transient (LVT) motors ($A_t/A_p \leq 0.56$, $L/D \leq 10$) and in the second phase high-velocity transient (HVT) motors ($A_t/A_p > 0.56$, $L/D > 10$) with nonuniform ports are considered for study. Figure 1 is demonstrating the influence of the port geometry on the axial velocity variations of five different LVT motor cases but with the same initial and boundary conditions. In the first three cases the divergent location (X_s) is varied, in the fourth case the inlet diameter is increased by 50%, and in the fifth case the divergence angle α is increased from 45 to 64 deg. All the results reported are anticipated and give corroborative evidences of the previous experimental and theoretical findings [6–8]. It can be seen from Fig. 1 that, in three different cases (cases 2, 3, and 5), the axial velocity is relatively high near the divergence

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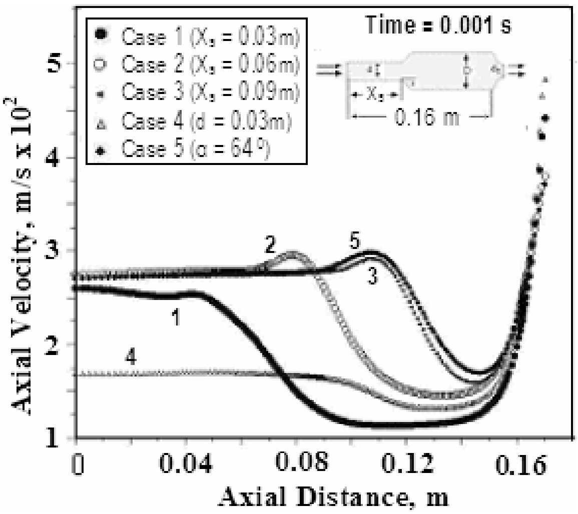

Fig. 1 Velocity variations along the axis of LVT motors showing the peak near the transition location (baseline values: $L/D = 4$, $X_s/d = 3$, $d_t/D = 0.375$).

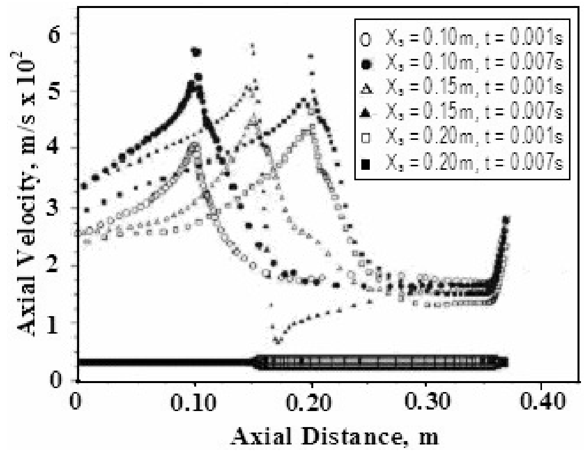

Fig. 2 Velocity magnitude along the axis of HVT motors showing the high peak near the transition region (a typical grid system is shown in the inset).

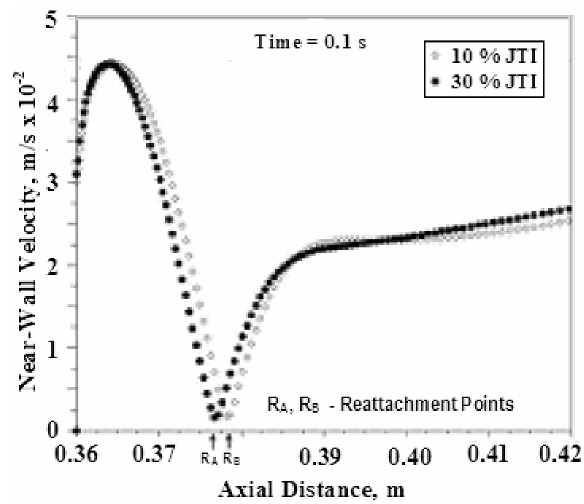

Fig. 3 Shifting of the reattachment point towards the step at high-turbulence level (enlarged view at the transition region of an HVT motor).

location. This can be explained with the help of boundary layer theory. Note that owing to the viscous friction, the boundary layer will be formed on the walls (before the transition region) and their thickness will increase in the downstream direction to the divergence location. Because the volume of flow must be the same for every section, the decrease in the rate of flow near the walls which is due to friction must be compensated by a corresponding increase near the axis. Thus the boundary layer growth occurs under the influence of an accelerated external flow. As a result, at larger distances from the inlet section velocity will be relatively high and the flow will possibly become turbulent; consequently the boundary layer thickness will suddenly increase leading to the sudden increase in the axial velocity due to the rocket motor port area fraction blocked by the boundary layer displacement thickness. This will cause flow separation far downstream of the divergence region. In the fourth case reported herein shown relatively low velocity at the axis due to the high port area compared to the other four cases reported. As stated in the Introduction increasing the port area of a solid rocket motor can reduce the unacceptable peak pressure, caused due to the gas dynamics of the upstream narrow port, at the expense of propellant loading density.

In the first case the flow recirculation tendency, leading to reattachment and secondary ignition, was found much less because the location of the transition region was near to the head end at the forfeit of the propellant loading density. When the transition location was fixed at far downstream of the SRM, the tendency of flow separation was found very high. This will lead to the formation of recirculation bubble and flow reattachment. Note that the flow reattachment will favor secondary ignition and that will cause the flow unsteadiness leading to an unacceptable high-pressure rise rate during the starting transient period of operation of solid rockets. Hence the prudent selection of the transition location within the given envelop, without diluting the high-performance nature of the solid rocket motor, is critical for a designer. This task will be more complex in the case of the HVT motor, which is discussed in the subsequent session.

In the second phase, HVT motors with three different transition locations (X_s) are considered. Figure 2 is demonstrating the difference in velocity magnitude along the axis of HVT motors with three different port geometries at two different time intervals but with the same initial and boundary conditions. In all the cases the velocity magnitude is found maximum at the transition location. As explained in the previous cases, in general, at larger distances from the inlet section (X_s) velocity will be high at the step location due to the boundary layer effect. But Fig. 2 shows that the peak value of the axial velocity is relatively lower in case 3 ($X_s = 0.20$ m) than case 2 ($X_s = 0.15$ m). This will not contradict the argument reported earlier based on boundary layer effect because this difference is due to the altered variation of the entire flowfield due to the nozzle end effect coupled with the geometry dependent driving forces and the corresponding compressibility effect. Through these diagnostic investigations, we observed that there is a limiting case of the location for transition for developing maximum axial velocity in any HVT motor due to its port geometry. In all the HVT motor cases, as anticipated, at the upstream the flow acceleration is found very high compared to the LVT motor cases reported earlier.

Note that the thickness of a turbulent boundary layer is larger than that of a laminar boundary layer owing to greater energy loss in the former. The development of the wall boundary layer in turbulent flow is more complicated than in wholly laminar flow. Initially it takes the form of a laminar layer, but at some position along the rocket motor port there is a transition to a turbulent layer, where a sudden increase in axial velocity can be discerned. The actual position of transition depends on a number of factors including Reynolds number, surface roughness, and the turbulence level of the igniter jet flow entering the motor port.

In another attempt with high L/D and X_s values, the influence of igniter jet turbulence intensity (JTI) on flow separation has been examined. A case with high-turbulence intensity shows less possibility of flow separation and reattachment. Figure 3 shows the near wall velocity viewing the tendency of the shifting of the reattachment point towards the step location at higher turbulence level. It has been observed that in all the cases the maximum

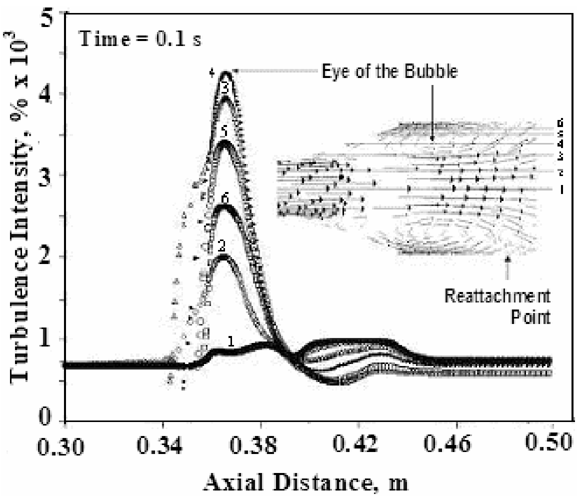

Fig. 4 Demonstrating the variation of the turbulence intensity along the axial direction of an HVT motor and pinpointing the fact that the turbulence intensity is maximum at the eye of the recirculation bubble (velocity vectors are shown in the inset).

turbulence intensity falls at the eye (not at the center point) of the recirculation bubble (see Fig. 4) because within the separation bubble, the mean turbulent intensity rises highly especially near the center of the bubble due to high mixing and large-scale unsteadiness, and it reduces as one move to the reattachment point and over the boundary layer development region.

Note that the secondary ignition occurs inside the initial recirculation bubble. Therefore, the size of the recirculation bubble and the location of the eye are important for further study. It is inferred that by inducing a high-turbulence level (practically by using igniter nozzle wire screens or by creating artificial roughness to the grain wall without affecting the ballistics), the position of transition could be brought closer to the entry region, or indeed the laminar layer could be entirely eliminated. Separation is mostly an undesirable phenomenon because it entails large energy losses.

Note that near to a solid surface flow velocities are low due to the no-slip condition at the wall. Hence in a region where the piezometric pressure is increasing, there are likely to exist certain streamlines, on which there are points whose total pressure is less than the piezometric pressure a little farther downstream. When this happens, these streamlines can only reach this further point if their energy is increased by the action of the shear force exerted by adjacent elements of the flow. This condition is satisfied when $\partial\tau/\partial y > 0$, where τ is the local shear stress and y is the distance measured away from the grain wall. This process of energy conversion by the action of viscosity cannot be maintained indefinitely and, if the flow does not manage to negotiate the region of adverse pressure gradient, a point is reached at which the value of τ and hence of $\partial u/\partial y$ becomes zero at the surface. Downstream of such a point, which is known as a separation point, the velocity u close to the surface becomes negative and so a region of reverse flow is established. Because of their ability to transfer momentum laterally, turbulent flows are more able than laminar flows to negotiate regions of adverse pressure gradients. Whether or not separation actually takes place, the general effect of the adverse pressure gradient is to give rise to a localized region of slow moving fluid stretching away from the wall. Because of the continuity condition, which can be applied over the whole cross-sectional area, the axial flow velocities must necessarily increase elsewhere to compensate for this effect. There is therefore a tendency for flows to become increasingly nonuniform whenever positive axial pressure gradients are encountered.

The separated flow characteristics such as size of the separation bubble, flow redevelopment, and heat transfer in the recirculation region are known to depend on Reynolds number upstream of the divergent region and its height. In the HVT motor cases considered here the reattachment point is found to lie around 1.5–3 times of the divergent height, as estimated, which is relatively higher than the LVT cases considered in this study. In the real motor test cases the exact location of the secondary ignition will possibly be altered from the reattachment point due to the additional influence of the igniter ballistics, ignition delay, and the propellant combustion. Therefore, for pinpointing the exact location of the secondary ignition one has to consider the intrinsic fluid dynamics and combustion aspects of the rocket motor and its allied igniter.

We also discerned that at the subsonic inflow conditions, the flow gets accelerated to a higher Mach number ($M \geq 1$) near the transition region of an HVT motor with divergent port but without any geometrical throat. A shock wave cannot exist unless the Mach number is supersonic; therefore the flow must have accelerated through a throat which is sonic. This is presumably due to the formation of the *fluid throat* at the beginning of the transition region due to the area fraction blocked by the boundary layer displacement thickness [9,10]. As a result the upstream narrow port of the DTM could act like a second igniter to the downstream port leading to the formation of the possible shock waves inside the motor during the starting transient period, which hitherto has been unexplored. Note that downstream of the shock the flow has an adverse pressure gradient, usually leading to wall boundary layer separation and reattachment. The shock waves in the HVT motor will alter the turbulence level and this new turbulence level will alter the location of reattachment and secondary ignition.

From these studies one can deduce that the thrust/pressure oscillations, pressure-rise rate, and unexpected peak pressure often observed in SRMs with nonuniform ports are presumably contributed due to the joint effects of the geometry dependent driving forces and the chamber gas dynamic forces. The present study is expected to aid the designer for conceiving the physical insight into problems associated with the prediction and the reduction of the peak pressure, the pressurization rate, and thrust oscillations during the starting transient period of operation of SRMs with nonuniform ports.

Conclusion

The fact that a separated flow region is formed downstream of a sudden expansion area is easy to appreciate. Rather less obvious is the fact the flow may separate from a surface which has no discontinuities of curvature. The process of separation is associated with large rates of dissipation of mechanical energy and so the avoidance of separation is an important factor in the design of internal flow systems. We concluded that due to the area fraction blocked by the boundary layer displacement thickness the SRMs axial velocity will be increasing up to a critical distance from the inlet section and further it will alter depending upon the port geometry and the nozzle end effect, which in turn alter the separation and secondary ignition. We also discerned the possibility of the shock waves inside the port of a rocket motor at the subsonic inflow condition due to the formation of the fluid throat as a result of the area fraction blocked by the boundary layer displacement thickness. The shock waves will alter the location of the reattachment point/secondary ignition and also enhance the heat flux to the propellant surface, which in turn enhance the flame spread rate and the transient burning. This will lead to the unexpected peak pressure, the pressure-rise rate, and the thrust oscillations during the mission of HVT motors with nonuniform port. We also concluded that the location of the reattachment point and/or secondary ignition and the features of the recirculation bubbles are sensitive to the igniter jet turbulence intensity. The implication of the secondary ignition can be quite serious for a practical rocket. Note that an error in pinpointing the secondary ignition can lead to significant errors in the thrust-transient prediction of SRMs. This is an area that needs to be contemplated in detail.

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